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LIFE SAFETY RISK ASSESSMENT FOR FIRECELLS WITH A SINGLE MEANS OF ESCAPE

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ABSTRACT

The Acceptable Solutions C/AS1 to the New Zealand Building Code impose a limit of 50 people that may be served by a single escape route. Restrictions are also placed on the travel distance between the most distant occupied space and the distance to reach the nearest safe path, safe place, or another firecell. These restrictions are related to the nature of the occupancy of the firecell, and the detection systems installed.

This report compares the requirements of the New Zealand Acceptable Solutions with other equivalent documents from the United Kingdom and the United States of America, and assess the escape times associated with the requirements. It then reviews the detection, pre-movement, tenability, and available escape times from various standard t^2 and item fires in a variety of firecell sizes, for a variety of occupancies, and quantifies the probability of successful egress from an open plan firecell with a single means of escape.

It is shown that if an adequate egress width is provided, the number of occupants in the room need not influence the time required to egress, but that the minimum door widths required by most approved documents will result in some queuing. Therefore, the limit of 50 people does not appear to result from a fire safety consideration, provided adequate egress widths are provided.

It is concluded that the risk of obstruction by the fire is generally small, with the most likely cause of failure being from loss of tenability in the firecell. The greatest chance of successful egress is from a large firecell, there being few successful outcomes from small firecells.

The provision of sprinklers has little effect on the tenability time in the firecell. There is some improvement in larger firecells, but not in those with smaller floor areas. The main benefit is in the control of the fire size, reducing the radiation levels and hence the risk of the fire obstructing the egress route.

Where fires are not sprinkler controlled, it is shown that the risk of obstruction is

typically low, although this result is only valid where there are multiple routes within the firecell leading to a single exit point.

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NOMENCLATURE

Abbreviations

DEOP	Dead End Open Path
TOP	Total Open Path
CL	Crowd, Large (>100 people)
CM	Crowd, Mercantile
CO	Crowd, Outside (external environment)
CS	Crowd, Small (<100 people)
SA	Sleeping, Hotel or transient accommodation
SC	Sleeping, in Care, such as a hospital, where occupants have reduced ability to care for themselves
SD	Sleeping, Detained, such as a prison
SR	Sleeping, Residential, being long term accommodation, either rented or owner occupied
WL	Working, Light Hazard
WM	Working, Medium Hazard
WH	Working, High Hazard
WF	Working, Ultra fast fire growth rate
NZBC	New Zealand Building Code
BIA	Building Industry Authority (New Zealand)

Definitions

Where appropriate, these definitions have been taken from the Acceptable Solutions C/AS1 to the New Zealand Building Code.

Dead End: That part of an *open path* where escape is possible in only one direction.

Horizontal Safe Path: A corridor which is a *safe path*

Occupancy: The purpose and population of the space. In the New Zealand Acceptable Solutions C/AS1 this is equivalent to the purpose group. The type of *occupancy* reflects the familiarity and alertness of the occupants, and the fire hazard associated with the purpose for which the space is used.

Open Path: That part of an escape route (including dead ends) within a firecell where occupants may be exposed to fire or smoke while making their escape.

Pre-movement time*:* The time after detection of the fire before movement related to evacuation starts. Actions by occupants during this time may include (but are not limited to) movement relating to collecting belongings, notifying others, and fire fighting behaviour.

Safe Path (also referred to in other codes as a Protected Path):That part of an exitway which is protected from the effects of fire by fire separations, external walls, or by distance when exposed to open air.

Safe Place: A place of safety in the vicinity of a building, from which people may safely disperse after escaping the effects of a fire. It may be a place such as a street, open space, public space or an adjacent building.

Total Open Path: Travel distance from starting point to a *safe path* or another firecell.

Symbols

a — A constant relating to the calculation of egress capacity, refer Equation 3.14

A_f — Floor area of firecell, m²

BL — Boundary Layer thickness, mm or m

c_p — Specific heat – for air this is 1.040 kJ/kg.K

c_s — Specific heat of skin, J/kg.K

D — Occupant density in escape routes, persons/m²

F_{sm} — Maximum specific flow in egress route, persons/s/m

g — Acceleration due to gravity, 9.81 m/s²

H — Height to the detector and/or ceiling, m

k — A constant relating to egress capacity, refer Equation 3.14

k_s — Thermal conductivity of skin, W/m.K refer Table 3.1

$\dot{m}_p$ — Mass flow of smoke in plume, kg/s

P — Number of people in firecell

$P_{S=1m}$ — Probability the separation distance between the fire and the egress route is 1 m or less

$P_{S=1\text{-}2m}$ — Probability the separation distance between the fire and the egress route is between 1 and 2 m

$P_{S=2\text{-}3m}$ — Probability the separation distance between the fire and the egress route is between 2 and 3 m

$P_{S>3m}$	Probability the separation distance between the fire and the egress route is 3 m or more
$\dot{q}''_r$	Incident radiation, kW/m²
$\dot{Q}$	Heat release rate of the fire, kW
$\dot{Q}^*$	Normalised heat release rate of fire, see Equation 3.3
RTI	Response time index, $(m/s)^{1/2}$
r	Radial distance of a detector from the fire plume, m
S	Travel speed, m/s
S	Separation distance between the fire and the escape route, m
$S.F$	Safety Factor
t	Time, s
$t_{lag,plume}$	Time for hot gases to rise in plume, s
$t_{lag,jet}$	Time for hot gases to travel to detector in ceiling jet, s
t_p	Time for occupants to pass through the door, s
t_{pre}	*Pre-movement* time, s
t_{sp}	Time for pain to be felt due to skin temperature, s
t_t	Travel time, s
T_D	Temperature of detector, K
T_{jet}	Temperature of hot gases in ceiling jet, K

$\overline{T}_p$ Average temperature of air in plume (K)

T_s Temperature of skin, K

T_∞ Ambient temperature, K

$T_{\infty s}$ Ambient temperature of skin, K, usually taken as 32.5 ºC

ΔT_D Change in detector temperature, K

v_{jet} Velocity of hot gases in the ceiling jet, m/s

W Width of escape route, mm

W_e Effective width of escape route, mm

W_{eff} Combination of factors affecting *pre-movement* time, refer Table 3.6

x Travel distance, m

x_s Basal layer depth in skin where pain is felt, 0.00008 m

x Minimum separation distance of egress route to fire, m

z Height above fire at which mass flow and temperature are determined, at the base of the hot layer (m)

α_s Thermal diffusivity of skin, m^2/s

λ_r Radiative proportion of energy emitted

ρ_∞ Density of ambient air, 1.1 kg/m^3

τ Detector response property

TABLE OF CONTENTS

TABLES

FIGURES

1 INTRODUCTION

The purpose of this study is to investigate the risk levels associated with single escape routes, review the acceptable, approved, and codified solutions documented in various national codes, and develop an alternative or specific design method for situations where the code based solutions appear to be inappropriate.

Statistics provided by the New Zealand Fire Service will be used to illustrate the actual risk level in existing New Zealand Buildings, and serve as a baseline for the risk analysis of the Acceptable Solutions to the New Zealand Building Code.

1.1 Escape from the Firecell of Fire Origin

As noted above, it is intended to investigate the risks to occupants in the firecell of fire origin where only a single escape route is provided. The New Zealand Acceptable Solutions C/AS1 to the Building Code permit up to 50 people to be served by a single horizontal escape route, and depending on the detection and/or suppression systems installed, the maximum *dead end open path* travel distance can vary from as little as 18 m to as much as 72 m. Where there is a choice of direction to different escape routes, longer travel distances are permitted.

The primary hazards for occupants in the same space are smoke and heat. Heat is usually fairly localised to radiation from the fire itself, although radiation from the hot smoke may also affect tenability. Where there is a single escape route from a space, the primary concern is whether the fire is too close to the escape route, and may prevent use of the route. Therefore the radiation from a fire near an escape route and the level of damage or pain caused by this radiation to the people using the escape route is to be assessed. This assessment is also to be combined with an assessment of the probability that the fire is in such a position where it may obstruct the egress route. Therefore the first step is to assess the size of fire that can be safely passed without causing pain at a separation distance from the escape route. The effect of travel speed (and hence the time that the person is exposed to the radiation) is also identified as a factor to be considered.

The other hazard for occupants in the firecell of fire origin is smoke. This is treated as a mixture of gases at a raised temperature. It usually includes oxygen, nitrogen, carbon dioxide, carbon monoxide, and soot as well as additional compounds related to the composition of the fuel. This hot layer tends to be hazardous to health when ingested if these constituents are present in sufficiently reduced (eg oxygen) or raised (CO_2, CO) quantities. Some may be more directly poisonous. The temperature of the layer can also cause damage to the lungs if too hot when inhaled. For the above reasons, the tenability of the space is assumed to be maintained only when the hot layer is above head height. A 2 m clearance from floor level is usually required, and is used in this analysis, to ensure that even tall occupants are considered and to ensure that the smoke is not being inhaled by any occupants.

To assess the tenability of the space, the level of the hot layer will be calculated from the volume of smoke flow in the plume, and it will be assumed to be evenly distributed throughout the ceiling space.

Finally, it is necessary to identify the time at which the fire is discovered, whether by a detection system or the occupants themselves, assess how much time might pass between detection and the decision to evacuate, and calculate how long is available for evacuation.

The above times can be difficult to determine with any degree of certainty. The detection time will vary depending on the size of the fire, the properties of the detector, and the location of the detector with respect to the fire. The greatest variation is when no automatic detectors are provided, and discovery of the fire is dependent on the occupants.

The time required by the occupants to decide to evacuate is also difficult to determine, with potential for significant variation, and is related to the occupants' alertness, their perception of the severity of the fire, and their commitment to their current activity.

The time available to escape is then the time remaining after the decision to evacuate, and before the conditions become untenable or the fire prevents use of the escape route. This time is expected to have a wide distribution, but which may be related to certain controllable conditions on which a specific design might be based.

1.2 @RISK

In this study, the primary tool in assessing the risks and their relative importance is a software package called @RISK, from Palisade (2003). It is an add-on to Microsoft EXCEL, so all the calculations are carried out in a spreadsheet environment, as well as permitting further manipulation of the results in Microsoft EXCEL.

Typically, spreadsheet analyses take a single set of input data, to provide a single set of results. @RISK expands this environment to allow a range of input data to be used, with a corresponding range of results. The input data, where there is some possible variation in the value (due to physical limitations, or possibly due to the requirement to consider a range of possibilities), may be assigned a distribution shape. For example, a normal bell curve distribution may be assigned to a detector parameter such as its RTI, and given a mean and standard deviation. The values of the RTI when taken over the whole number of repetitions of the analysis can then be seen to have this distribution. Each value is determined using the Monte Carlo technique. In this study, each analysis of an item fire typically involves 500 repetitions of the calculations, each with different sets of input data. In addition to these repetitions, different scenarios may also be defined. In this study a total of 5 scenarios are considered for each fire, each involving different detector configurations (with different activation temperatures and spacings). For each set of input data, the calculations are also carried out for each of these five scenarios. Therefore, for each analysis a total of 2500 sets of output results are produced and have been analysed.

1.3 Literature Review

A search of literature relating to single escape routes did not reveal a great depth of published information. Barnett (1987) reviews the separation required between different egress routes (to allow them to be defined as separate), but is based on densely occupied escape routes, and relatively slow travel speeds. Further, it does not address a developing fire, or even the tenability time in the firecell.

2 EGRESS VIA SINGLE ESCAPE ROUTES – CODE REQUIREMENTS

New Zealand was one of the first countries in which specific fire engineering design was permitted, with the New Zealand Building Code in 1992 permitting the development of alternative designs instead of following the earlier prescriptive code. The New Zealand Building Code states the primary requirements for fire safety in clauses C1, C2, C3 and C4. These requirements are given in the form of objectives, not prescriptive rules, and are included in the Appendices, Section 9. One means of compliance with the Building Code requirements may be achieved through producing a fire design that complies with the Acceptable Solutions C/AS1, published by the Building Industry Authority (2001). Given the range of situations to which the solutions may be applied, there is some variation, but generally the requirements are given in a prescriptive form. These Acceptable Solutions include a selection of rules and numbers which can not easily be quantified, and little justification for the limits are provided. Therefore, as most fire safety designs use the Acceptable Solutions C/AS1 as the initial foundation for the design, with specific design only undertaken for particular aspects and comparison with the Acceptable Solutions, it can be difficult to propose an alternative design which is contrary to these particular rules.

The purpose of this study is to assess the background and design implications to the rule that limits the number of people who may be served by a single means of escape to 50, restricts the length of their path to reach that escape, and permits increases in that path length when automatic fire detection and/or suppression systems are installed.

As such rules are not usually isolated in their occurrence, similar limitations are expected to occur in other design codes around the world. Section 3 identifies and compares the limits placed by various fire safety code documents on the number of people that may be in a *dead end* space, ie one with a single escape route, and any restrictions on that route.

2.1 New Zealand Acceptable Solutions C/AS1

The limit placed by the New Zealand Acceptable Solutions C/AS1 on the number of people served by a single escape route is 50 people.

Maximum permissible travel distances vary with the *occupancy* of the space. They are usually defined by the familiarity of the occupants with the space, their environmental awareness (awake, asleep), the fire hazard, and the alarm system provided to notify them of fire. In shops and hotels, where occupants are not expected to be familiar with escape routes from the space, travel distances are slightly reduced. This reduction appears to be related to greater numbers of people using escape routes, resulting in greater congestions and slower travel speeds. Working and residential spaces, where familiarity is greatest, and fewer people are present, have the greatest permissible travel distances. Even greater travel distances are permissible when the space is only intermittently occupied (such as plant rooms, recognising the lower probability of a space being occupied during a fire and the faster travel speed of the few people who may be present). Where significant quantities of highly combustible goods are stored (likely to result in an ultra fast fire growth rate), the permitted travel distance is significantly reduced. Where occupants may be sleeping, and are restrained (either by disability, age, health, or detention), both smoke detectors and sprinklers are mandatory.

As noted earlier, the travel distances permitted are limited by the choice of directions available. If escape is only possible in only one direction, the travel distance to either reach a *safe place* or a choice of egress routes is defined as *dead end open path* length. If two directions of escape are possible, then the distance to reach a *safe path* or *safe place* is called *total open path* length.

The escape route widths from such spaces are required as follows – for horizontal travel, allow 7 mm per person, but no less than 700 mm total width. Where there are more than 50 people, or disabled people may be present, the minimum width is 850 mm. Therefore, a route of 850 mm wide may serve up to 121 people if there is also a second way out. Door frames may impinge up to 125 mm on the required width of the escape route, although the minimum clear open width of the door is 600 mm for a 700 mm wide route, and 760 mm for a 850 mm wide route.

The permissible travel distances, both *dead end open path* and *total open path*, including the allowable increases for different means of detection are summarised in Table 2.1. Where both smoke detectors and sprinklers are installed, the travel distance benefits are usually additive.

Separated escape routes, ie where there are two or more open paths, are defined as follows in the Acceptable Solutions, paragraph 3.8.3:

> **Where two or more open paths are required, they shall be separated from each other, and remain separated until reaching an exitway or final exit. Separation shall be achieved by diverging (from the point where two escape routes are required), at an angle no less than 90° until separated by:**
>
> **a) A distance of at least 8.0 m, or**
>
> **b) Smoke separations and smoke control doors.**

2.2 Scottish Regulations:

The Scottish Regulations (Building Regulations: Technical Standards Part E) allow a minimum of 60 people to be served by a single escape route.

The separation required between the two routes is defined as follows:

> **Where more than one exit is required the directions of travel from any point within the storey or space must –**

a) diverge at an angle of at least 45º

b) diverge at an angle of less than 45º but be protected from each other by a wall or partition

i) having at least 30 minutes fire resistance; and

ii) with any opening which is protected by a fire door having at least 30 minutes fire resistance; or

c) be combined for a distance not exceeding that allowed for a single direction of travel and then diverge to 2 exits at an angle of at least 45º plus 21/20 for every metre in the single direction of travel, except –

where more than one exit is required from a room, storey or space each exit must be separated from the other as if the distance allowed for single direction of travel did not extend outwith the room, storey or space.

Escape route widths are based on the requirement for 5.3 mm per person, but not less than 1000 mm if serving up to 100 people. The door on such an escape route may reduce this width to a minimum of 750 mm.

The permissible escape route lengths for the Scottish Regulations are given in Table 2.2.

2.3 England & Wales Regulations:

The legislative background for England and Wales appears to be similar to New Zealand. The Approved Documents are one way, but not the only way, of meeting the requirements of the Building Regulations. These approved documents allow 60 people in a *dead end*, provided that the storey exit can be reached within the *dead end* travel distance limit. The number of people is reduced to 30 in Institutional residential *occupancies* (2A in these regulations, equivalent to SC and SD in the New Zealand Acceptable Solutions).

Horizontal travel and vertical travel widths are required to be 5 mm per occupant, but not less than 750 mm for up to 50 people, or 850 mm per exit for 110 people. *Dead end* travel distance limits are given in Table 2.3. Similarly to the Scottish Regulations, *dead end* travel finishes when egress routes diverge at 45º (rather than 90º as required by the New Zealand Acceptable Solutions).

2.4 USA Requirements (from UBC 1997)

UBC 1997 typically allows no more than 50 people in a *dead end*, but the number does vary with the *occupancy*. *Occupancies* with the 50 limit include assembly areas, classrooms, and shops. The permissible travel distances and numbers of people in *dead end* spaces for this code are summarised in Table 2.4. Travel path widths for horizontal travel require 5.08 mm per person, but for hazardous *occupancies*, this is doubled (10.16 mm per person). Doors serving 10 or more people to be 914 mm nominal width, or 813 mm clear width.

It should be noted that unlike the other codes described above, the travel distances for *dead end* travel not are reduced from those for non-*dead end* travel.

Access to exits is not permitted to be interrupted by intervening rooms (not including foyers etc), unless there is only one way out of the room.

2.5 USA Requirements from NFPA 101: Life Safety Code 2000

The following requirements were obtained from Coté (2000), the Life Safety Code Handbook, which in addition to containing the complete text of NFPA 101, also includes a commentary.

In this code, a “dead end” and a “common path of travel” have two slightly different definitions. The definitions from the Life Safety Handbook, paragraph A.7.5.1.6, are as follows:

> **A common path of travel exists where a space is arranged so that occupants within that space are able to travel in only one direction to reach any of the exits or to reach the point at which the occupants have the choice of two paths of travel to remote exits.**
>
> **While a dead end is similar to a common path of travel, a dead end can exist where there is no path of travel from an occupied space but can also exist where an occupant enters a corridor thinking there is an exit at the end and, finding none, is forced to retrace his or her path to reach a choice of exits.**

In the following text, the term *dead end* will be used to refer to the "common path of travel" situation defined above, this being the meaning of the term as used in most other documents, particularly including the Acceptable Solutions to the New Zealand Building Code.

Typically, some benefit is given where sprinklers are installed, but there is no such effect where an automatic fire alarm system is provided. Often, while sprinklers are indicated as a requirement, the option of not providing them appears to be available due to the alternative travel distance limits where they are not installed.

Dual escape routes are typically required from each floor, however there is typically no limit given within the text for the number of people who may be within a *dead end* or "common path of travel" within the floor, and there are no rules covering the required divergence of escape routes. The limit is on the actual travel distance. Travel distances and *occupancy* information from this code is given in Table 2.5.

Occupancy Description		Dead End Open Path (m)				Total Open Path (m)				Route Width Allowances	
		Manual	Heat	Smoke	Sprinkler	Manual	Heat	Smoke	Sprinkler	Corridor	Door
Working, Normal Hazard	WL	24	28.8	48	48	60	72	120	120	7 mm/p 850 mm	760 mm
Working, High Hazard	WH	12	12	12	24	30	30	30	60	7 mm/p 850 mm	760 mm
Working, intermittent service only	IA	36	43.2	72	72	72	86.4	144	144	7 mm/p 850 mm	760 mm
Public, inside (including shops)	CS, CL, CM	18	21.2	36	36	45	54	90	90	7 mm/p 850 mm	760 mm
Public, in open air	CO	36	36	36	36	90	90	90	90	7 mm/p 850 mm	760 mm
Sleeping, familiar (rented apartment, or own home)	SR, SH[1]	24	26.4	36	36	60	66	90	90	7 mm/p 850 mm	760 mm
Sleeping, unfamiliar (hotel etc)	SA	18	20	36	36	45	50	67.5	67.5	7 mm/p 850 mm	760 mm
Sleeping, detained or in care	SC, SD	NP[2]	NP	18[2]	18[2]	NP	NP	45	45	7 mm/p 1200 mm	1200 mm

Table 2.1 : New Zealand Acceptable Solutions C/AS1 for Single Means of Escape

Note: 1. Where an evacuation scheme is required to be approved by the NZ Fire Service (typically when there are more than 3 household units in the building) a local alerting smoke alarm is usually required.

2. NP = Not Permitted – all SC and SD *occupancies* are required to be sprinklered and have smoke detectors.

Occupancy (description)	NZ equivalent Purpose Group	Permitted travel distance in *Dead End* (m)	Permitted Total Open Path travel distance (m)	Path Widths	
				Corridor	Door
Institutional	SC, SD	9 – 15	18 – 32	5.3 mm/p 1200 mm	750 mm
Residential	SA, SR	15	32	5.3 mm/p 1000 mm	750 mm
Flats and Maisonettes sub-group	SA, SR	7.5 m from front door to stair	30 m from front door to stair	5.3 mm/p 1000 mm	750 mm
Shops and Commercial	CS, CM, and WL	15, but only 9 m within a mall less than 3 storeys high	32	5.3 mm/p 1200 mm	750 mm
Assembly (not part of SC), including schools	CL	15	32	5.3 mm/p 1000 mm	750 mm
Industrial	WL	18	45	5.3 mm/p 1000 mm	750 mm
Low hazard storage	WL/IA	18-30	45	5.3 mm/p 1000 mm	750 mm
High hazard storage	WF/ID	15-18	32-45	5.3 mm/p 1000 mm	750 mm
Open sided carparks	IA	18	45	5.3 mm/p 1000 mm	750 mm
Rooftop plantroom	IA	60	100	5.3 mm/p 1000 mm	750 mm

Table 2.2 : Scottish Regulations on Escape Routes

Occupancy (description)	NZ equivalent Purpose Group	Dead end open path Travel Distance (m)	Total Open Path Travel Distance (m)	Corridor Widths
Institutional, including recreational facilities	SC, SD	9	18	5 mm/p 750 mm for 50 people, 850 mm for 110 people 1050 mm for 220 people
Other Residential (bedrooms)	SA, SR	9	18	5 mm/p 750 mm for 50 850 mm for 110 1050 mm for 220
Office	WL	18	45	5 mm/p 750 mm for 50 850 mm for 110 1050 mm for 220
Shop and Commercial	CM	18	45	5 mm/p 750 mm for 50 850 mm for 110 1050 mm for 220
Assembly and Recreation, including schools	CL	18	32-45	5 mm/p 750 mm for 50 850 mm for 110 1050 mm for 220
Industrial	WL	25	45	5 mm/p 750 mm for 50 850 mm for 110 1050 mm for 220

Storage	IA/ID	25	45	5 mm/p 750 mm for 50 850 mm for 110 1050 mm for 220
High hazard	WF	9	18	5 mm/p 750 mm for 50 850 mm for 110 1050 mm for 220
Plant Room, including open air	IA	9-60	35-100	5 mm/p 750 mm for 50 850 mm for 110 1050 mm for 220

Table 2.3 : English and Welsh Escape Routes

Description of Occupancy	NZ Equivalent Purpose Group	Number of People permitted in *Dead end*	Open Path Length	Open Path Length with Smoke Detectors	Open Path Length with sprinklers	Egress Route Widths
Assembly	CS/CL	50 (though only 10 if on a balcony)	60.96 m	60.96 m	76.2 m	5.08 mm/p 914 mm < 50 1118 mm > 50
Business	WL	30	60.96 m	60.96 m	76.2 m	5.08 mm/p 914 mm < 50 1118 mm > 50
Educational	CS/CL	50	22.86 m	27.432 m	33.528 m	5.08 mm/p 914 mm < 50 1118 mm > 50
Institutional	SC/SD	6-10	30.48 m	30.48 m	76.2 m	5.08 mm/p 914 mm < 50 1118 mm > 50
Mercantile	CM	50	60.96 m	60.96 m	76.2 m	5.08 mm/p 914 mm < 50 1118 mm > 50
Residential	SR/SA	10	60.96 m	60.96 m	76.2 m	5.08 mm/p 914 mm < 50 1118 mm > 50

Table 2.4 : UBC 1997 Means of Escape Requirements

Description of Occupancy	NZ Equivalent Purpose Group	Number of People permitted in *Dead end*	*Dead End* Path Length	Dead End Path Length with sprinklers	Total Open Path Length	Total Open Path Length with sprinklers	Corridor Widths
Assembly	CL	50 on a balcony, otherwise no limit	6.1 m if > 50 people 23 m if < 50 people	6.1 m if > 50 people 23 m if < 50 people	45 m	60 m	5 mm/p 810 mm door
Educational	CL	no limit indicated, although each level requires 2 means of escape	23 m	30 m	45 m	60 m	5 mm/p 810 mm door
Day-Care	CS	no limit indicated, but each level requires 2 means of escape	23 m	30 m	45 m	60 m	5 mm/p 810 mm door
Health Care	SC	no limit indicated, however each level requires 2 means of escape	up to 30 m, with corridor dead end limit of 9.1 m	up to 30 m, with corridor dead end limit of 9.1 m	45 m	60 m	5 mm/p if sprinklers 13 mm/p if no sprinklers 810 mm door

Description of Occupancy	NZ Equivalent Purpose Group	Number of People permitted in *Dead end*	*Dead End* Path Length	Dead End Path Length with sprinklers	Total Open Path Length	Total Open Path Length with sprinklers	Travel Path Widths
Ambulatory Health Care	SC	at least 2 exits required from each floor, but no indication of number of people in a dead end	23 m	30 m	45 m	60 m	5 mm/p 810 mm door
Detention and Correctional	SD	at least 2 exits required from each floor, but no indication of number of people in a dead end	15 m	30 m	45 m	60 m	5 mm/p 810 mm door
Residential – Hotels	SA	2 exits from each sleeping room unless sprinklers provided	10.7 m	15 m	53 m	99 m	5 mm/p 810 mm door
Residential – Apartments	SR	2 exits from each sleeping room unless sprinklers provided.	10.7 m	15 m	53 m	99 m	5 mm/p 810 mm door

Description of Occupancy	NZ Equivalent Purpose Group	Number of People permitted in *Dead end*	*Dead End* Path Length	Dead End Path Length with sprinklers	Total Open Path Length	Total Open Path Length with sprinklers	Travel Path Widths
Residential – Board and Care, small, new & existing	SA	2 escape routes required from each storey, and two escape routes from each sleeping room. Sprinklers usually required	no limit	no limit	no limit	no limit	5 mm/p 810 mm door
Residential – Board and Care, large, new	SA	2 escape routes required from each storey, and two escape routes from each sleeping room. Sprinklers usually required	not applicable (not permitted)	38 m	(not permitted)	99 m	5 mm/p 810 mm door
Residential – Board and Care, large, existing	SA	2 escape routes required from each storey, and two escape routes from each sleeping room. Sprinklers usually required	33 m	49 m	53 m	99 m	5 mm/p 810 mm door
Mercantile	CM	no limit on numbers, provided travel distance requirements met	23 m	30 m	30 m	60 m	5 mm/p 810 mm door

Description of Occupancy	NZ Equivalent Purpose Group	Number of People permitted in *Dead end*	*Dead End* Path Length	Dead End Path Length with sprinklers	Total Open Path Length	Total Open Path Length with sprinklers	Travel Path Widths
Business	WL	up to 100 people may be served by a single horizontal route, provided total travel distance to exterior within the limit, and no other spaces using exitway. Or up to 30 people each level, using and sharing stairs, no higher than 3rd floor.	23 m	30 m	60 m	91 m	5 mm/p 810 mm door
Industrial	WL-WF	typically 2 exits from each level. Low and ordinary hazard permitted to have single if within dead end limit	15 m (0 m if high hazard)	30 m (15 m if high hazard)	23 – 90 m depending on hazard	23 – 122 m depending on hazard	5 mm/p 10 mm/p if high hazard 810 mm door
Storage	WM	As with industrial situations, low hazard storage occupancies permitted to have single escape route. Ordinary hazard escape route required to be within dead end limit.	15 m (0 m if high hazard) no limits for low hazard	0 – 30 m depending on hazard no limits for low hazard	23 –60 m depending on hazard no limit for low hazard	30 – 122 m depending on hazard no limit for low hazard	5 mm/p 10 mm/p if high hazard 810 mm door

Table 2.5 : NFPA 101 Means of Escape Requirements

2.6 Comparison of the Codes

A comparison of *dead end* and *total open path* travel distance limits for different *occupancies* and detection methods, including number of people who are permitted to be provided with only a single means of escape is given in Table 2.6 and Table 2.7.

These show that the New Zealand Acceptable Solutions place the most weight on the benefits of automatic alarm and suppression systems – the only other Codes which make any allowances for these are the UBC and NFPA 101, which permit increased travel distances in certain *occupancies* where smoke detectors or sprinklers are provided.

The UBC has the greatest range of permitted numbers of occupants in a *dead end*, varying from 6 to 50. The England & Wales Documents permit up to 60 people in a *dead end* in all groups, except for institutional purpose groups where this is reduced to 30. The New Zealand Acceptable Solutions and the Scottish Regulations each have single limits of 50 and 60 respectively. The life safety code, NFPA 101 places few limits on the numbers of people served by a "common path of travel", requiring them to only be within an appropriate travel distance. Up to 100 people in a working environment may be served by a single escape route provided travel distances are within relatively stringent limits.

Egress widths appear to have little variation, although there is some difference in the way doors are treated. For New Zealand, Scotland and the UBC, doors are permitted to reduce the width of the egress route, but no such allowance is mentioned in the Approved Documents for use in England and Wales or in the NFPA Life Safety Code. This, however, is reflected in the required width of the egress route. These route widths are also dependent on accessibility requirements, particularly for wheelchair users. For simplicity, all the widths shown in the tables assume that provision for disabled users is not required in this situation, particularly as the requirements for these provisions are not stated in the fire egress documents. The obstruction or reduction of an egress route by a door way is usually permitted because it is recognised that it is not reasonable to fit a doorway into a corridor and achieve the same clear opening width as the width of the corridor. Further, reference to Nelson & MacLennan (1995) indicates that there are varying boundary layer widths to different elements within an egress route. The effective design width of a corridor or ramp is 400 mm less than the clear width, while the effective design width of a door or archway is only 300 mm less than the clear width of the frame. This implies that a door or archway may reduce the clear width of the egress route by up to 100 mm (ie 50 mm each side) without reducing the effective design width and hence the route capacity.

2.7 Egress Times

Finally, consider how the various provisions described above correspond to evacuation times. There are two periods of egress that contribute to the egress time. The first of these is the time required to travel to the door, and the second is the time associated with queuing to pass through the door along with the other occupants of the room. It is usually assumed that the occupants are evenly spread throughout the space, so the first person will tend to reach the door almost immediately. If the time required for the last person from the most remote corner of the room to reach the door is greater than the queuing time, there will be no queue left by the time they reach the door, and the egress time is the travel time. If the queuing time is greater than that travel time, then it is assumed that a queue is formed almost immediately, and that the egress time is dependent solely on the queuing time. These times are given in Table 2.8. The calculations have been undertaken using the principles described by Nelson and MacLennan (1995), and initially appeared to indicate that where 50 people are required to pass through a 600 mm wide door, the egress time may exceed 2 minutes, as illustrated in Equation 2.1.

$$W_e = W - 2 \cdot BL = 0.6m - 2 \cdot 0.15m = 0.3m \qquad \text{Equation 2.1}$$
$$t_p = \frac{P}{F_{sm} \cdot W_e} = \frac{50}{1.3 \cdot 0.3} = 128 \sec$$

Where:

Table 3-14.5 in Nelson MacLennan (1995) indicates that the maximum specific flow through a door, F_{sm} is 1.3 persons/s/m of effective width, and

The typical boundary layer thickness for a door is 15 cm (0.15 m).

However, this boundary layer appears to be excessive in the calculation of the effective width for these doors, and it is proposed that the effective width should not be taken less than 530 mm. A local constriction to no less than this width permits one person to pass without restricting speed. Even so, the queuing time for 50 people (refer Table 2.8) is typically 1¼ to 1½ minutes, in comparison to a travel time of ½ a minute or less.

The travel times are calculated using a travel speed of 1.2 m/s for low density *occupancies* such as work places. Where the occupant density is higher, such as in crowd *occupancies*, this speed is reduced to 0.8 m/s. For more information on the background to selection of these travel speeds, refer to section 3.6.

This indicates that the travel distances have little or no effect on the evacuation times for this magnitude of occupant load, and it raises the question whether increases in travel distance due to automatic detector installation are really effective in maintaining a similar level of life safety. In fact, for most of the situations in the table, the travel distance only starts controlling the egress time when the occupant load is 20 people or fewer (this is the number given in the second to last column of Table 2.8, based on the travel distances permitted where no automatic detectors are installed). Only the wider path widths required by UBC come closest to not controlling the egress rate, and even with those widths, the travel distances are still 40% shorter than would result in those controlling egress times. Considering the possibility of slower travel speeds, these could be as low as 0.1 m/s, and often as low as 0.3 m/s before queuing is avoided.

To avoid queuing, door widths of 2-3 m are typically required (as indicated in Table 2.8), and would clearly have the advantage of ensuring greater separation between someone egressing and a possible fire.

One of the few possible arguments for allowing increased egress distances where automatic detection is provided, is that assuming a relatively even distribution of occupants throughout a space with a single escape route, is that where manual detection only is provided, occupants are required to be closer to the escape route, and hence may have an increased awareness of a fire that threatens this. This argument cannot easily be addressed, except to indicate that in the following study, awareness of the fire by occupants is assumed to be triggered by smoke that spreads throughout the space, rather than by cues associated with proximity to a fire. There is also some doubt as to whether cues other than smoke would be effective for occupants permitted to be 20 m from the location of the fire (a possible situation complying with the Acceptable Solutions).

This report will review the separation required between a fire and the escape route to permit egress, though will not specifically address the separation between two separate escape routes.

Occupancy Type	Code	No. in *dead end*	*Dead end open paths*				Total Open Paths				Door Width	Path width
			Man.	Heat	Smoke	Spr.	Man.	Heat	Smoke	Spr.		
Working – Normal Hazard	NZ	50	24	28.8	48	48	60	72	120	120	760	850
	Scot	60	15-18	15-18	15-18	15-18	32-45	32-45	32-45	32-45	750	1000
	Eng. & Wales	60	18	18	18	18	45	45	45	45	750	750
	UBC	30	60.96	60.96	60.96	76.2	60.96	60.96	60.96	76.2	813	914
	NFPA 101	NL	23	23	23	30	60	60	60	91	810	810
Small Crowd / Public Gathering	NZ	50	18	21.2	36	36	45	54	90	90	760	850
	Scot	60	15	15	15	15	32	32	32	32	750	1000
	Eng. & Wales	60	15-18	15-18	15-18	15-18	32-45	32-45	32-45	32-45	750	750
	UBC	50	60.96	60.96	60.96	76.2	60.96	60.96	60.96	76.2	813	914
	NFPA 101	NL	6.1, 23	6.1, 23	6.1, 23	6.1 or 23	45	45	45	60	810	810
Shops	NZ	50	18	21.2	36	36	45	54	90	90	760	850
	Scot	60	9-15	9-15	9-15	9-15	32	32	32	32	750	1000
	Eng. & Wales	60	18	18	18	18	45	45	45	45	750	750
	UBC	50	60.96	60.96	60.96	76.2	60.96	60.96	60.96	76.2	813	914
	NFPA 101	NL	23	23	23	30	30	30	30	60	810	810
Schools	NZ	50	18	21.2	36	36	45	54	90	90	760	850
	Scot	60	15	15	15	15	32	32	32	32	750	1000
	Eng. & Wales	60	18	18	18	18	45	45	45	45	1600	1600
	UBC	50	22.86	22.86	27.4	33.6	45.7	45.7	53.3	68.6	813	914
	NFPA 101	NL	23	23	23	30	45	45	45	60	810	810

Table 2.6 : Comparison of Codes - Active Purpose Groups

Occupancy Type	Code	No. in *dead end*	*Dead end open path*				Total Open Path				Door width	Path width
			Man.	Heat	Smoke	Spr.	Man.	Heat	Smoke	Spr.		
Motel/Hotel type accommodation	NZ	50	18	20	36	36	45	49.5	67.5	67.5	760	850
	Scot	60	15	15	15	15	32	32	32	32	750	1000
	Eng. & Wales	60	9	9	9	9	18	18	18	18	750	750
	UBC	10	61	61	61	76.2	61	61	61	76.2	813	914
	NFPA 101	NL	10.7	10.7	10.7	15	53	53	53	99	810	810
Apartments and Long Term Accommodation	NZ	50	24	26.4	36	36	60	66	90	90	760	850
	Scot	60	15	15	15	15	32	32	32	32	750	1000
	Eng. & Wales	60	9	9	9	9	18	18	18	18	75	750
	UBC	10	61	61	61	76.2	61	61	61	76.2	813	914
	NFPA 101	NL	10.7	10.7	10.7	15	53	53	53	99	810	810
Hospitals, Prisons	NZ	50	NP	NP	18	18	NP	NP	45	45	760	850
	Scot	60	9-15	9-15	9-15	9-15	18-32	18-32	18-32	18-32	750	1000
	Eng. & Wales	60	9	9	9	9	18	18	18	18	750	1000
	UBC	6-10	30.48	30.48	30.48	76.2	30.48	30.48	30.48	76.2	813 (1118 for beds)	914
	NFPA 101	NL	15-30	15-30	15-30	30	45	45	45	60	810	810

Table 2.7: Comparison of Codes - Sleeping Purpose Groups

Occupancy Type	Code	No. in *dead end*	*Dead end open path* Travel Time (s)				Total Open Path Travel Time (s)				Door Flow time (s)	Critical Number (manual alarm)	Door Width reqd (mm)
			Man.	Heat	Smoke	Spr.	Man.	Heat	Smoke	Spr.			
Working – Normal Hazard	New Zealand	50	20	24	40	40	50	60	100	100	128	13	2223
	Scot	60	13	13	13	13	27	27	27	27	103	8	3992
	Eng. & Wales	60	15	15	15	15	38	38	38	38	132	10	3377
	UBC	30	51	51	51	64	51	51	51	64	45	35	754
	NFPA 101	(50)	19	19	19	25	50	50	50	76	94	13	2307
Small Crowd / Public Gathering	NZ	50	23	27	45	45	56	68	113	113	128	15	2009
	Scot	60	19	19	19	19	40	40	40	40	103	12	2762
	Eng. & Wales	60	19	19	19	19	40	40	40	40	132	12	2762
	UBC	50	76	76	76	95	76	76	76	95	75	52	805
	NFPA 101	(50)	8	8	8	8	56	56	56	75	94	5	5344
Shops	NZ	50	23	27	45	45	56	68	113	113	128	15	2009
	Scot	60	11	11	11	11	40	40	40	40	103	7	4403
	Eng. & Wales	60	23	23	23	23	56	56	56	56	132	15	2351
	UBC	50	76	76	76	95	76	76	76	95	75	52	805
	NFPA 101	(50)	29	29	29	38	38	38	38	75	94	19	1638
Schools	NZ	50	23	27	45	45	56	68	113	113	128	15	2009
	Scot	60	19	19	19	19	40	40	40	40	103	12	2762
	Eng. & Wales	60	23	23	23	23	56	56	56	56	38	35	2351
	UBC	50	29	29	34	42	57	57	67	86	75	19	1646
	NFPA 101	NL	29	29	29	38	56	56	56	75	94	19	1638

Table 2.8 : Comparison of Codes Egress Times from Active Occupancies using Nelson MacLennan

3 ESCAPE FROM THE FIRECELL OF FIRE ORIGIN

There are a number of factors that affect the characteristics of the fire, the conditions in the firecell, and the likely response of the occupants of the firecell, which all need to be identified as part of the analysis.

In considering the occupant avoidance behaviour, the following phases of awareness must be addressed. Firstly, there is the means of detection of the fire, whether by the occupants or by automatic detectors, resulting in a warning to other occupants. Then, the reaction to that notification needs to be considered, and how long it might take the occupants of the firecell to decide to move. Finally, the actual movement time must be considered, both the travel time to the door, and the time required for everyone to pass through the door out of the space.

Whether the evacuation is successful or not depends on whether tenability is maintained while people are still in the firecell, and whether the fire obstructs the route, either directly or through excessive radiation from an adjacent location.

Tenability is related to exposure of the occupants to smoke and heat from the fire. It is dependent on the object which is burning, and hence tends to be related to the use of the firecell. Similarly, the *occupancy* type also affects the *pre-movement* time and hence the time required to evacuate the firecell. Where there is only a single escape route, the critical scenario is expected to be due to skin damage from radiation from a fire immediately adjacent to the escape route, although this may not be the only cause of failure to evacuate. This assumption has been made because of the dramatic increase permitted in the *total open path* travel distance during which the occupants are assumed to be exposed to smoke, but are free to move away from the vicinity of the fire.

The approach followed in this assessment is as follows:

Assume a single, open plan room, being the firecell.

For a variety of room geometries, first identify the conditions that will mean that the room is no longer tenable. These will be in the form of a hot layer height and temperature, and a level of heat radiation to the egress route from a fire near the exit.

From these conditions, various fire scenarios can be analysed to find at what time these conditions are reached. These scenarios will include standard t^2 fires, as well as results from fire tests of typical items, such as those published by Särdqvist (1993), and those on the NIST web-site (2002). For each scenario, the alerting time can be determined for each type of detector (occupant, heat detector, smoke detector, or even sprinkler). In the case of a sprinkler system, the effect of the sprinkler on the fire heat release rate must be considered. Here, it will conservatively be assumed that it will control the fire, ie preventing further increase of the heat release rate, maintaining it at the level reached at sprinkler activation. Finally, this leaves the time available for evacuation (including *pre-movement* activities). The time required for *pre-movement* activities can vary hugely, and may be influenced by the occupants' perception of danger. As this perception is difficult to quantify, let alone its effect on the *pre-movement* time, the effect of conditions in the firecell will not generally be taken on the *pre-movement* time. This then leaves the time available for evacuation. It is intended to compare the actual evacuation times available to assess egress requirements in the form of total occupant numbers, egress distances, and escape route widths.

The following sections address the above points, and provide the background to the spreadsheet tools which have been developed for this study. As has been noted earlier, many of the parameters have been assigned a distribution to allow the influence of each property on the final result to be determined.

3.1 The Room

First, it is necessary to determine a physical environment in which to place the occupants and the fire. For simplicity, the firecell is assumed to be a single space without full height partitions, and having several routes within the space to reach the single egress door. This provides a single volume for the smoke to fill. Subdivision of the space by full height partitions could delay occupant awareness of the fire if it occurred within an unoccupied space, and smoke movement through the space would also be influenced by the arrangement of partitions and openings. For the assessment of travel distances, orthogonal travel is assumed. This is travel from a point 1 m from the furthest corner of the room, to the door in the corner diagonally opposite, first travelling across the room, then turning through 90º to travel directly to the door. This conservatively allows for movement around partitions and furniture. The plan dimensions of this room will be assumed to be between 5 m and 25 m, and the ceiling height between 2.4 m and 3.5 m high.

3.2 Requirements for Successful Evacuation

There are two products of fire that may prevent people from evacuating from a space. The first of these is the hot layer, which may descend below head height, obscuring visibility and endangering the health of occupants who may inhale it. Even if it does not descend to this level, the temperature of the hot layer may result in exposure of the occupants to excessive radiation. The second is radiation from a fire in front of or adjacent to the final exit, preventing occupants from passing it to get out of the room.

3.2.1 Smoke Layer

As noted previously, when the hot layer descends below 2 m, conditions in the firecell are assumed to be untenable.

To calculate the predicted smoke layer thickness and height, particularly for non-t² fires, the smoke production rates, and hence the filling rates must be assessed. A method for doing this is given by Cooper (1995) based on first principles.

The total mass flow in the plume, and the temperature of the plume at a distance z above the fire can be estimated using the following equations:

$$\dot{m}_p = 0.210\rho_\infty (gz)^{1/2} z^2 \left(\dot{Q}^*\right)^{1/3}$$ Equation 3.1

$$\frac{\overline{T}_p}{T_\infty} - 1 = \frac{\left(\dot{Q}^*\right)^{2/3}}{0.210}$$ Equation 3.2

Where the heat release rate is normalised as in Equation 3.3.

$$\dot{Q}^* = \frac{(1-\lambda_r)\dot{Q}}{\rho_\infty c_p T_\infty (gz)^{1/2} z^2}$$ Equation 3.3

The overall temperature of the hot layer can be calculated by determining the total mass, volume, and hence the density, which can then be related to an average temperature. Radiation from the hot layer is assessed in the next section.

3.2.2 Radiation

Radiation from a fire, or from any other source, causes the skin to increase in temperature, and the level of pain, or severity of damage in extreme cases is related to the temperature of the skin.

The SFPE (2000) has, in reference to work carried out by a variety of people, developed and documented a method by which the damage to skin may be predicted. Experiments have been carried out correlating the time to pain in relation to the exposure to radiant heat flux, and also identifying when burn damage starts to occur. The temperature of the skin can be related both to the level of pain, and to the level of damage experienced by the skin. An equation has been developed allowing the temperature of the skin to be calculated at any depth after exposure to constant radiant heat flux for a certain period of time. Pain has been shown not occur where the heat flux is less than 1.7 kW/m². The thermal response of the skin, which is governed by the thermal inertia, varies with the radiation intensity. Pain is broadly related to skin temperature, with burn damage generally occurring when the temperature reaches 44 ºC at 80μm depth below the skin surface. At lower radiation exposure levels, 10% of the damage may be done during the cooling period, and at higher radiation levels, the cooling period can account for up to 35% of the damage. As it is assumed that temperatures should not reach these levels in the first place because this would mean failure of the design, and skin temperature should not continue to rise once the heat source is removed, it has not be considered necessary to include for cooling. Equation 3.4 gives the relationship between skin temperature, exposure time, and flux levels.

$$T_s = T_{\infty s} + \frac{\dot{q}_r''}{k_s}\left[\frac{2\sqrt{\alpha_s t}}{\sqrt{\pi}}\exp\left(-\frac{x_s^2}{4\alpha_s t}\right) - x_s \cdot erfc\left(\frac{x_s}{2\sqrt{\alpha_s t}}\right)\right]$$ Equation 3.4

where $\alpha_s = \dfrac{k_s}{\rho_s c_s}$

A simpler correlation, given in Equation 3.5, calculates the time to pain that is recommended for use in design.

$$t_p = \frac{1}{S.F.}\left(\frac{35{,}000}{\dot{q}_r''}\right)^{1.33}$$ Equation 3.5

Where *S.F.* is the safety factor (2 if $\dot{q}_r''$ < 6 kW/m², 4 if $\dot{q}_r''$ > 6 kW/m²)

A safety factor is usually required to be used in the fire safety design, however this is not appropriate for a study of this nature, in which all the effects are to be combined without prejudice to one means of failure or another, giving everything a balanced weighting. In this study, it will be conservatively assumed that the exposure time will be taken as the time that the occupant is exposed to any radiation flux greater than 1.7 kW/m². The flux level will be taken as the maximum flux level during that time.

Skin Properties are given in Table 3.1, as determined by Weaver and Stoll, reported in SFPE (2000). Although thermal conductivity was found to vary with temperature, and whether or not the skin is being heated or cooled, it was shown that a constant value during heating provided satisfactory results that compared well with the experimental data.

Property	Symbol	Value	Units
Thermal Conductivity	k_s	0.5878	W/m-K
Volumetric Heat Capacity	$\rho_s c_s$	4,186,800	J/m³-K
Basal Layer Depth (at which pain occurs)	x_s	0.00008	m

Table 3.1 : Skin Properties

The actual temperature of the skin is then compared with the temperature at which damage starts occurring, 44 ºC. When it is predicted that this temperature will be exceeded, evacuation is assumed to be unsuccessful.

An assessment of the skin temperatures for passing fires of various sizes using the different equations with and without safety factors has lead to the generation of the graph in Figure 3.1.

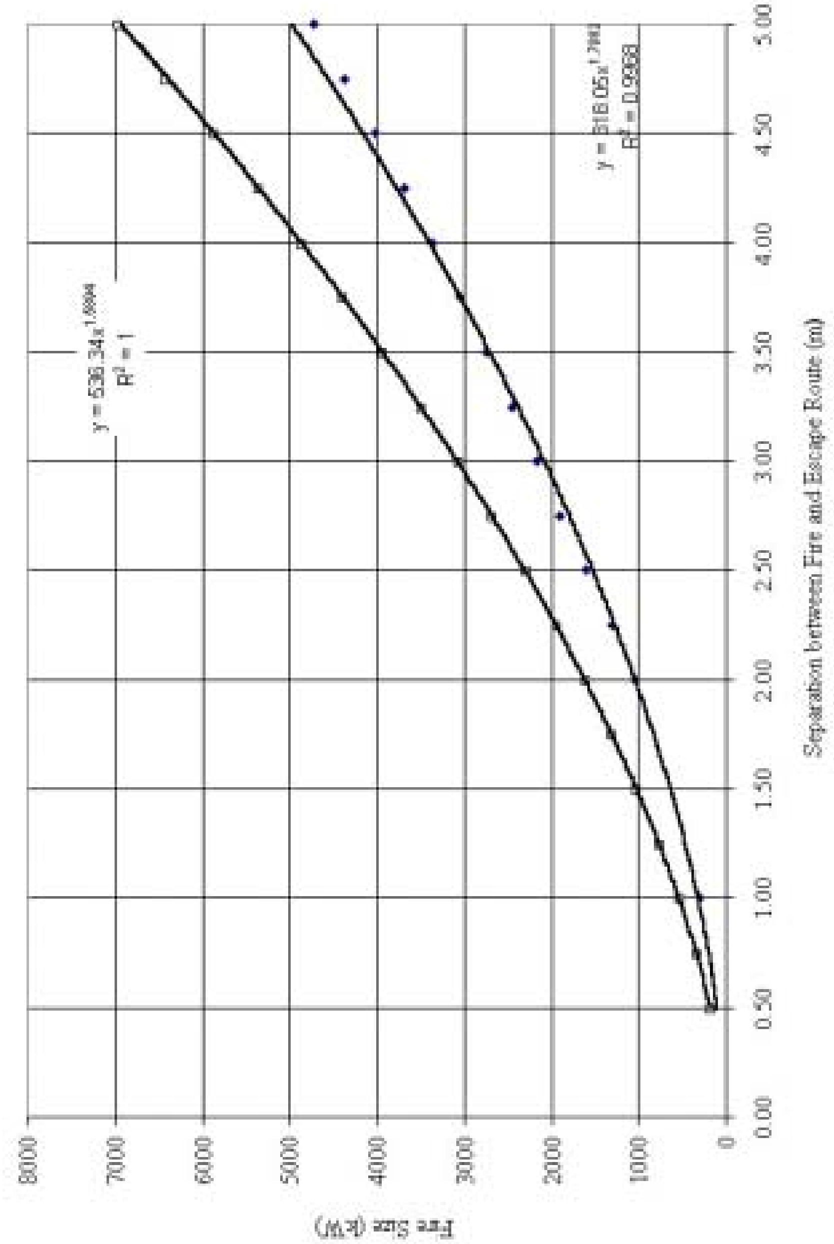

Figure 3.1 : Fire Size and Travel Speed to Successfully Pass at a Range of Separations

A similar calculation can be undertaken to assess skin temperature response to radiation from the hot layer. However, review of the results indicates that it is simpler to limit the radiation flux to 2.5 kW/m², for which the time to pain is approximately 30 seconds.

3.2.3 Combination Effects

Finally, much of the following sections relating to single escape routes from a firecell assume that the fire is located close to the final escape point from the firecell. The actual probability of the fire occurring, and also occurring in such a location should be put into context, by assessing the area in which this fire could occur and comparing it to the total area within the firecell. The probability of a fire in that location versus any other location in the firecell can therefore be related to the area of the room being considered.

In a specific design, it should also be possible to consider the actual layout of the space, and particular types of furniture that may be positioned in that location, eg work-stations, chairs, or sofas. Data on these particular items can be sourced from a report prepared by Särdqvist (1993), and from the NIST web-site.

3.3 Means of Detection

This will depend on the detectors installed, their location relative to the fire, and the characteristics of the fire. If no detectors are installed, then the occupants are required to become the detection system. There is little published guidance on when a fire is most likely to be manually detected, so it will be necessary to make an assumption based on alertness of occupants, and cues available to occupants.

3.3.1 Automatic Detection by Heat Detectors and Sprinklers

Activation of heat detectors and sprinklers may be predicted through predicting their temperatures when exposed to a time dependent fire. In this assessment, the method will be that used by the DETACT procedure in FPETool, described by Deal (1994). Equation 3.6 gives the ceiling jet temperatures and velocities, assuming the detector (conservatively) is outside the plume impingement region.

$$T_{jet} = T_{\infty} + \frac{5.38}{z}\left(\frac{\dot{Q}}{r}\right)^{2/3}$$ Equation 3.6

$$v_{jet} = 0.2\frac{\dot{Q}^{1/3} z^{1/2}}{r^{5/6}}$$

For each time step, the above temperatures and velocities are calculated, and the temperature of the detector is calculated using the following relationship (also from Deal (1994)). Note that this equation actually gives the temperature rise experienced by the detector (rather than the detector temperature at the new time) per unit time exposure to the gas flow. The new detector temperature is therefore calculated using the relationship given in Equation 3.9. Although the results are not as accurate for longer time steps, they are still within approximately 10% of the times calculated by FPETool. The verification of these calculations has been carried out in Appendices, Section 10.

$$\Delta T_D = \left(T_{jet,t+\Delta t} - T_{D,t}\right)\left(1 - e^{-\frac{1}{\tau}}\right) + \left(T_{jet,t+\Delta t} - T_{jet,t}\right)\tau\left(e^{-\frac{1}{\tau}} + \frac{1}{\tau} - 1\right)$$ Equation 3.7

$$\tau = \frac{RTI}{\sqrt{v_{jet,t}}}$$ Equation 3.8

$$T_{D,t+\Delta t} = T_{D,t} + \frac{1}{2}\left(\Delta T_{D,t} + \Delta T_{D,t+\Delta t}\right)\cdot \Delta t$$ Equation 3.9

The time required for the smoke in the plume to travel from the fire to the detector, usually known as the lag time, can be calculated using Mowrer and Newman, as described by Schifiliti et al (1995), with the relationships given in Equation 3.10.

$$t_{lag,plume} = \frac{0.66H^{4/3}}{\dot{Q}^{1/3}}$$ Equation 3.10

$$t_{lag,ceilingjet} = \frac{4.61r}{\left(\dot{Q}/H\right)^{1/3}}$$

These lag times are usually small in comparison to the detector activation time, but are given for completeness.

The properties of heat detectors as used in the analysis are given in Table 3.2.

Variable	Distribution	Mean	Standard Deviation	Any truncations
Activation temperature, T_{act}	normal	57 ºC	2 ºC	
RTI	normal	20 $m^{½}s^{½}$	5 $m^{½}s^{½}$	max: 25 $m^{½}s^{½}$ min: 15 $m^{½}s^{½}$
Detector Spacing, S	Scenarios with spacings of 2, 3, 4, 5 & 6 m are considered.			

Table 3.2 : Heat Detection Variables

Note: For compliance with the Fire Alarm Standard, NZS 4512, heat detectors are supposed to cover a maximum area of 36m². Therefore, the spacing range has been taken as 2 to 6 m centres.

For sprinkler activation, the range of variables in Table 3.3 is used, with specific scenarios as in Table 3.4.

Variable	Distribution	Mean	Standard Deviation
Activation temperature, T_{act}	normal	67 ºC	2 ºC
RTI	Scenarios with RTI of 80 (fast response) and 120 (intermediate response) heads are considered most likely		
Head Spacing where compliance with NZS4541 is appropriate, S	Scenarios at spacings of 2, 3, & 4 m are reviewed.		

Table 3.3 : Sprinkler System Variables

Scenario	Head Spacing (m)	RTI $(m/s)^{1/2}$
1	2	100
2	3	80
3	3	100
4	4	100
5	4	120

Table 3.4 : Sprinkler System Scenarios

3.3.2 Smoke Detector Activation

While smoke detector activation can be predicted through considering the optical density of smoke, the usual correlation involves assuming activation of the detector after a temperature rise of 13 ºC. Schifiliti (1995) notes this as being typically valid for flaming fires where such a temperature rise would be expected. Such an assumption would not predict detector activation for a smouldering fire. For the fires considered in this study, there is sometimes an initial smouldering period, followed by flaming combustion. In these situations, provided that the quantity of smoke produced is not greater than that usually associated with the low heat release rate (ie resulting in no reduction in tenability time), the smoke detector activation time calculated may be long, giving a shorter escape time than might otherwise be available. Note that the RTI is greater than would usually be used in FPETool, however the larger value is required to maintain stability in the calculation where the time step is 20 seconds or more. In FPETool, a time step for calculation is usually 1 second, which tends to maintain stability for the smaller RTI value.

Variable	Distribution	Mean	Standard Deviation
Activation temperature T_{act}	normal	33 ºC	1 ºC
RTI	constant	5 $m^{½}s^{½}$	
Spacing	Scenarios include spacings of 6, 7, 8, 9 & 10 m.		

Table 3.5 : Smoke Detector Characteristics

The New Zealand Standard, NZS4512, covering the installation of alarm systems usually requires the installation of smoke detectors so that the area covered by a detector is no greater than 90 m^2. This code may be contravened by specific design, and the intention of these scenarios is to determine how the spacing affects the detection time, and assess how this affects the time available for evacuation.

3.3.3 Manual Detection

For manual detection, particularly in larger spaces, smoke is the cue most likely to lead to detection of the fire. It is therefore necessary to look at how the smoke layer develops, and track its height as part of the tenability study.

It has been proposed in some specific fire engineering designs, that detection is possible when the depth of the smoke layer in the occupied room reaches 5-10% of the ceiling height (or 15-20% of the ceiling height in big spaces). However, care should be taken in utilising this approach – "can occur" does not mean "will occur". In this analysis, as occupants are generally expected to be alert, a range of detection times will be considered, from when the smoke layer depth reaches 5% of the ceiling height, to when it reaches 20% of the ceiling height. It has also been noted that at these times, the radiation from the smoke layer to head height is elevated. As it does not seem reasonable for someone not to notice when they are exposed to radiation equivalent to that received from the sun at the equator (ie 1 kW/m^2), radiation from the smoke layer will also be included as a means of detection. The minimum radiation detection level will be taken as 0.8 kW/m^2 received, the average is 1 kW/m^2, and the maximum is 1.2 kW/m^2. The effect of the range of detection times will be considered in the same way that the different automatic detection scenarios are addressed.

Magnusson (1995) has also suggested an alternative approach. Where direct awareness of the fire (due to proximity) is likely, the detection may be based on a lognormal distribution with a mean of 10 seconds and a standard deviation of 5. Where this proximity is not the case (possibly due to subdivision of the firecell into rooms), a survey of fire officers by Magnusson has suggested that the manual detection time should be approximately twice that of an automatic detection time. The type of detector is not identified. While many of the standardised situations may be single rooms, this will not necessarily describe all cases. Therefore, the method proposed above relating to the thickness of the smoke layer is suggested as an appropriate median between the two scenarios for the general assessment.

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Deleted: Now, consider at what stage the fire may actually be discovered due to the smoke. As was noted above, detection of smoke can reasonably be related to the thickness of the layer. To account for the large range in possible detection times, it is suggested that the mean detection time the time when the thickness of the smoke layer

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Deleted: may be achieved by using a normal distribution with a standard deviation of 20% of the mean detection time. The distribution is truncated with a minimum detection time being that at which the smoke layer thickness reaches 5% of the ceiling height,

Deleted: and a maximum of the time for it to reach head height. ¶

3.4 Automatic Suppression by Sprinklers

Sprinkler activation may be predicted as noted above, using the procedure for heat detector activation. Fire behaviour after sprinkler activation is typically assumed to be controlled – ie the fire size does not grow, but continues at the size reached when the sprinklers activated.

3.5 Pre-Movement Time

There have been several methods developed relating to the assessment of *pre-movement* time, however few codes, if any, recommend specific methods to be used. Most methods compare the length of the *pre-movement* time with the information available to the occupant of the firecell, with few providing any absolute guidance. Sime (1996) identifies that there are a number of factors that determine how long a group of people will take to respond to the information available through the alarm system, and start evacuating, with the factors considered as indicated in Table 3.6.

Sime's paper also indicates that much further work is needed to verify and calibrate the *pre-movement* times suggested in this paper, however despite this warning, it is known to have been used as part of specific fire engineering designs in New Zealand.

Although Sime does not identify the effect of direct exposure to the fire cues in case of a fire in a firecell, it is considered reasonable to compare this with the 'directive announcements'. Alerting will occur through activation of either a detector, or of a manual call point by someone close by, so the remaining occupants can be expected to be alerted both by the alarm bell, and by fire cues with the combination of these "cues" providing as much information as might be provided by live directive public announcements to someone remote from the fire.

Table 3.7 illustrates the assessment of *pre-movement* times for each of the *occupancies* considered in this study. These include an office (used as an example of a work environment), a shop (as an example of a crowd environment, where occupants are already moving), and a bar (as an example of a crowd environment where people are seated, and will tend to take longer to respond).

A uniform distribution has been assigned to the factors B to I, and the basic time A has been given a normal distribution with a standard deviation of 10 seconds.

Factor	Title	Description and Effect
A	Communications	This factor affects the minimum baseline *pre-movement* time, and is based on the alarm system. These are assumed to range from an alarm bell, through 'non-directive' prerecorded PA announcements, Informative warning visual displays, and/or live 'directive' PA announcements from a control room, possibly incorporating CCTV.
The sum of the following factors is inversely related to the *pre-movement* time		
B	Alertness	asleep 1 → 5 awake
C	Mobility	low (eg disabled) 1 → 5 high (able bodied)
D	Social Affiliation	group 1 → 5 alone (note that a family group will tend to take longer to respond, with group dynamics tending to retard individual action)
E	Role	public 1 → 5 staff (staff, who tend to have greater responsibility for a situation, and who may have relevant training are will tend to respond quicker than the general public)
F	Position	lying 1 → 5 moving
G	Commitment	high 1 → 5 low (a commitment to finish an action, eg completing a purchase, will tend to delay evacuation)
H	Focal Point	none 1 → 5 focused (if attention tends to be focused in one direction, eg a theatre, like commitment to an activity, this will tend to delay response)
I	Familiarity	unfamiliar 1 → 5 familiar (choosing the route via which to evacuate will take less time if the occupants are familiar with the choices)

Table 3.6 : Factors Affecting Pre-Movement Times

It has been attempted to relate the effect of the fire size at the time of occupant discovery to the *pre-movement* time using the following method:

- Where the detection is better than average (ie the smoke layer depth is 5% of the ceiling height), the larger value of W_{eff}, and hence a longer *pre-movement* time is used. Note that the basic response time is still normally distributed as described above.

- Where the manual detection time is longer than average (ie the hot layer depth is 20% of the ceiling height), the shorter value of W_{eff}, and hence a shorter *pre-movement* time is used.

- Where the average manual detection is used (ie hot layer is 10% of the ceiling height), the average value of W_{eff}, and hence an average *pre-movement* time is used.

- For automatic detection devices, the full distribution is considered, with both the range of factors B to I, as well as the distribution of the basic *pre-movement* time, A is used.

The *pre-movement* time, t_{pre}, is then calculated using the following relationships:

$$W_{eff} = 5/Avg(B \ldots I) \quad \text{Equation 3.11}$$

$$t_{pre} = A \times W_{eff} \quad \text{Equation 3.12}$$

The resulting distribution of the *pre-movement* time, t_{pre}, is closest to a normal distribution, which is illustrated in Figure 3.2, being the *pre-movement* times for an office *occupancy*. This also shows that the distribution is relatively tight, as indicated by the small standard deviation relative to the mean.

Factor Range	Occupancy		
	Working – Office (WL)	Mobile Crowd - Shop (CM)	Seated Crowd - Bar (CS)
A	60±30 sec	60±30 sec	60±30 sec
B	4→5	4→5	2→4
C	4→5	2→4	2→4
D	3→5	2→4	1→3
E	4→5	1→3	1→3
F	1→3	3→5	1→3
G	1→3	1→3	1→2
H	1→3	1→3	1→3
I	4→5	1→3	2→4
Avg (B…I) ±std dev	28.0±1.18	27.6±1.15	22.5±1.49
W_{eff}	1.43	1.79	2.18
t_{pre} (minutes & seconds ±standard deviation)	1:26±4	1:47±7	2:11±11

Table 3.7 : Pre-movement Time Calculation

Further work by Sime has also postulated that additional factors such as population density, visual access, enclosure, and complexity of the environment will also affect the response of the occupants. The effect of these is difficult, if not impossible to assess for the generalised situations being considered in this project.

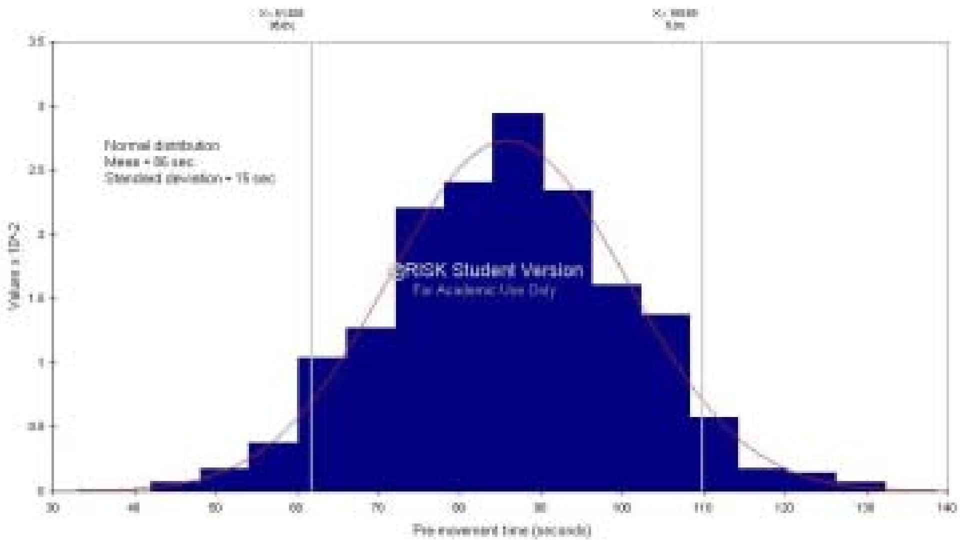

Figure 3.2 : Pre-Movement Time Distribution – Office Occupancy

New Zealand Legislation, in particular the Fire Service Act, has resulted in the requirement that buildings providing accommodation for more than 3 household units, or being a place of work for more than 10 people, shall have an evacuation procedure. Among the requirements of the evacuation procedure, which must be approved by the New Zealand Fire Service, include the carrying out of 6 monthly trial evacuations. Trial evacuations are usually unannounced to the majority of the occupants, although the Building Warden is usually notified. This process is generally adequate to ensure that all occupants can identify the sound of the building fire alarm system (and are unlikely to ascribe another meaning to it), and are familiar with the egress routes. In such cases, particularly in office tenancies observed by the author, *pre-movement* times can be as little as 15-30 seconds.

3.6 The Effect of Travel Distance on Travel Time

The calculation of evacuation times is carried out using Nelson MacLennan (1995). The effect of occupant density on the evacuation speed is to be assessed based on Fruin's "Levels of Service". The densities and flows associated with these levels of service are given in Table 3.8.

Fruins Level of Service		Walkway	
		American Units	Metric Conversion
A	Flow volume: Average Speed: Occupant Density: % of Capacity:	7 [1] 260 [2] 35 [3] 25% [4]	2.1 [5] 1.32 [6] 0.31 [7]
B	Flow volume: Average Speed: Occupant Density: % of Capacity:	7-10 250-260 25-35 35%	2.1-3.0 1.27-1.32 0.31-0.43
C	Flow volume: Average Speed: Occupant Density: % of Capacity:	10-15 230-250 15-25 40-65%	3.0-4.6 1.17-1.27 0.43-0.72
D	Flow volume: Average Speed: Occupant Density: % of Capacity:	15-20 200-230 10-15 65-80%	4.6-6.1 1.01-1.17 0.72-1.08
E	Flow volume: Average Speed: Occupant Density: % of Capacity:	20-25 110-200 5-10 100%	6.1-7.6 0.56-1.01 1.08-2.16
F	Flow volume: Average Speed: Occupant Density: % of Capacity:	>25 0-110 <5 sporadic	>7.6 0-0.56 >2.16

Table 3.8 : Fruins Levels of Service

Notes: 1. Units are pedestrians per foot width of corridor or stair per minute

2. Speed in ft/min

3. Density in sq.ft/person

4. Flow at this level of service is given as a percentage of the maximum capacity of the corridor or stair.

5. Metric units are pedestrians per metre width per minute

6. Metric speeds in m/s

7. Densities in occupants/m²

The level of service typically assumed for egress routes is ‘C’, and will be used in this analysis. However, for higher density *occupancies*, such as crowd environments, this may be un-conservative. Therefore, working *occupancies* will be assumed to be level of service C with a travel speed of 1.2 m/s, while bars and shops will have level of service E, and a travel speed of 0.8 m/s.

The time to travel to the door, t_t is calculated using Equation 3.13:

$t_t = x / S$ Equation 3.13

where x = *the travel distance (m).*

3.7 The Effect On Evacuation Time of the Number of People in the Space

As noted in section 3.6, the travel speed is affected by the density of people on the egress routes, and hence will affect travel time. However, the size of the doors can also have a significant effect on the difference in egress time between the first and the last occupant.

As the occupants will be generally assumed to be distributed fairly evenly throughout the space, the total time required to exit through the door will be taken as the greatest of the travel distance from the furthest corner of the room, t_t, and the flow time through the door, t_p.

The flow time is calculated using similar assumption to those in the travel time calculations, based on work by Nelson & Maclennan (1995), giving the following expression for the time for a number of people to pass through a door, t_p.

$$t_p = \frac{P}{1 - aD} kDW_e$$ Equation 3.14

where P = number of people

D = density of people (persons/m²)

a = 0.266 (a constant)

k = 1.4 (a constant for horizontal travel)

W_e = effective width of the door (m), being the clear width less 150 mm, but no
less than 530 mm.

The maximum travel time for a group of people will be determined from the room size, and influenced by the level of service, and the time required for everyone to pass through the door to the space outside. To assess the total time required for a group of people to egress from a space, particularly where they are fairly evenly distributed throughout the space, the following assumptions can be made:

- If the time required to travel from the furthest occupied area to the door is greater than the time required for everyone to flow through the door, there will be no queue when the most distant occupant arrives, and they can pass straight through the door. The time required to egress is therefore the travel time.

- If the time required for everyone to pass through the door is greater than the time required for the most distant person to join the queue, then the egress time will be equal to the flow time. This assumes that the first person has not had to travel any distance to initiate the queue. If there is any initial travel distance for the first occupant before the queue can form, then the time associated with this travel distance should be included in the flow time.

In this generic assessment, it will be assumed that there is no initial travel time, so the egress time is taken as the greatest of either the flow time or the travel time for the most distant occupant.

As the evacuation time available is known, the arrangement of the egress route (being the travel distance and the route width) will determine the number of people able to escape in the time available.

4 RISK ASSESSMENT OF ESCAPE FROM FIRECELL OF FIRE ORIGIN

4.1 t² Design Fires

The following sections illustrate the trends observed in the analysis of the t^2 fires. These fires are standard fires, which are based on the assumption that the fire size is proportional to the square of the time after ignition. The rate of growth is also related to the time taken for the fire to reach an output of 1 MW. A fire with a slow growth rate reaches this size in 600 seconds, a medium growth rate in 300 seconds, fast in 150 seconds, and ultra-fast in 75 seconds. The fire size relationship to time for these fires is given in Equation 4.1.

Equation 4.1

$$Slow: Q = \left(\frac{t}{600}\right)^2 (MW)$$

$$Medium: Q = \left(\frac{t}{300}\right)^2 (MW)$$

$$Fast: Q = \left(\frac{t}{150}\right)^2 (MW)$$

$$Ultra-Fast: Q = \left(\frac{t}{75}\right)^2 (MW)$$

4.1.1 Detection Times and Room Tenability

A relationship between manual detection times, tenability times, and firecell size is expected due to these being affected by the volume available for smoke storage near the ceiling of the room. Automatic detector activation (including sprinklers) is not dependent on the room size as the correlations used assume an unconfined ceiling. Instead these times are dependent on the ceiling height and detector spacing. These relationships are illustrated in Figure 4.1, Figure 4.2, Figure 4.3, and Figure 4.4 for a medium fire growth rate. Figure 4.1 indicates that the assumption of a relationship between manual detection, tenability, and floor area of the firecell is significant. The relationship is closer to linear when the travel distance is substituted for the floor area in Figure 4.2. Note that the travel distance here is as defined in Section 3, being the sum of the length and breadth of the room, less 2 m. While there is some spread, it appears likely that this is due to the effect of the time-step used, in addition to some influence of the ceiling height. Figure 4.3 shows that the time-step used in the calculation of the automatic detector activation times is too large for the ceiling height effects to be observable here. The graph does, however, indicate the more significant difference in detector operation times for the different spacings. Where the spacings are reduced, detection times can be reduced by as much as 1 minute from those achieved by detectors at the maximum compliant spacing. Figure 4.4 shows that when sprinklers operate, the expectation of a dependence of tenability time on room area is confirmed. Refer to Section 3.3.1 for a definition of the sprinkler spacings and types included in each scenario.

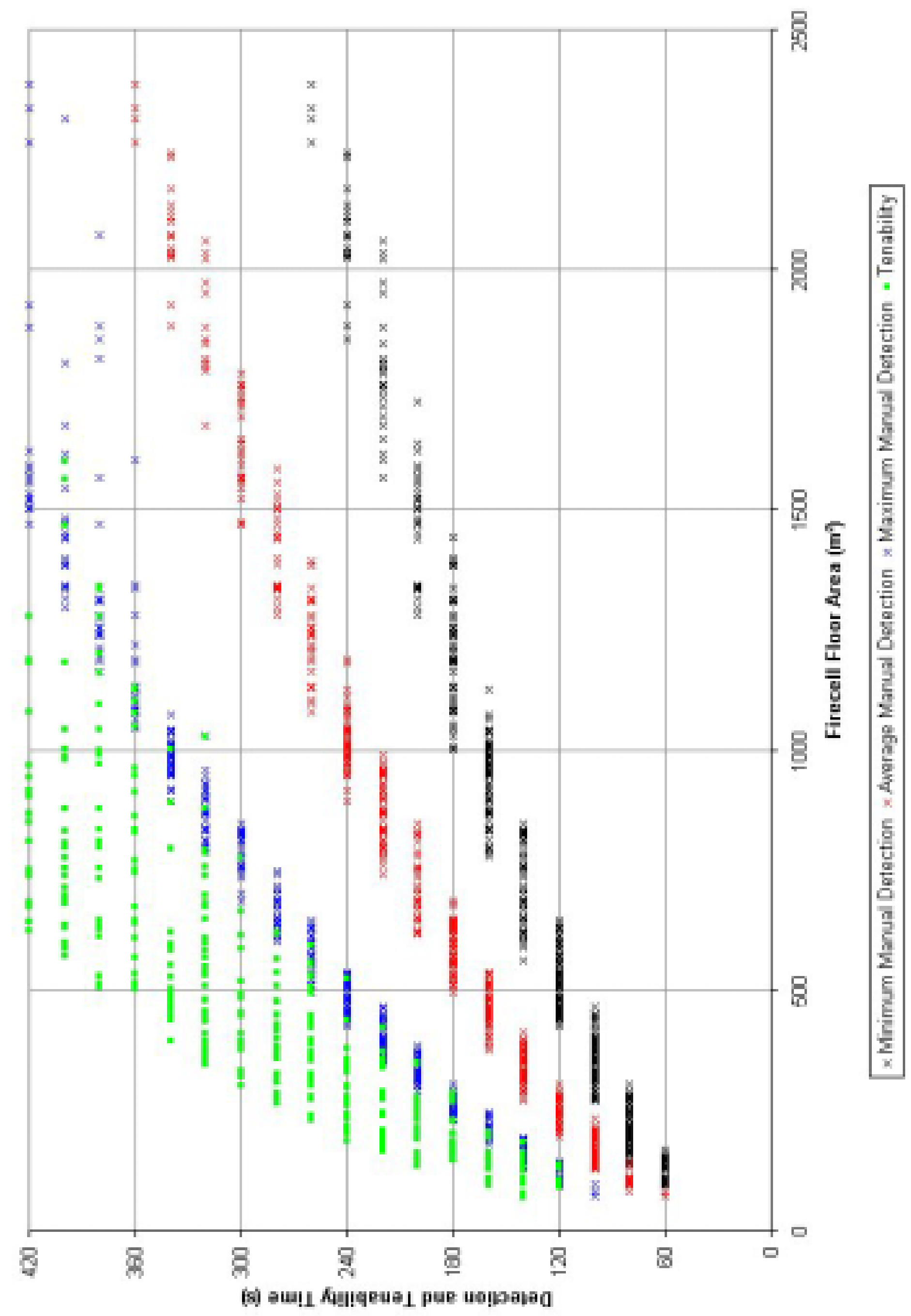

Figure 4.1 : Manual Detection Times and Tenability vs Room Area for Medium Fire Growth Rate

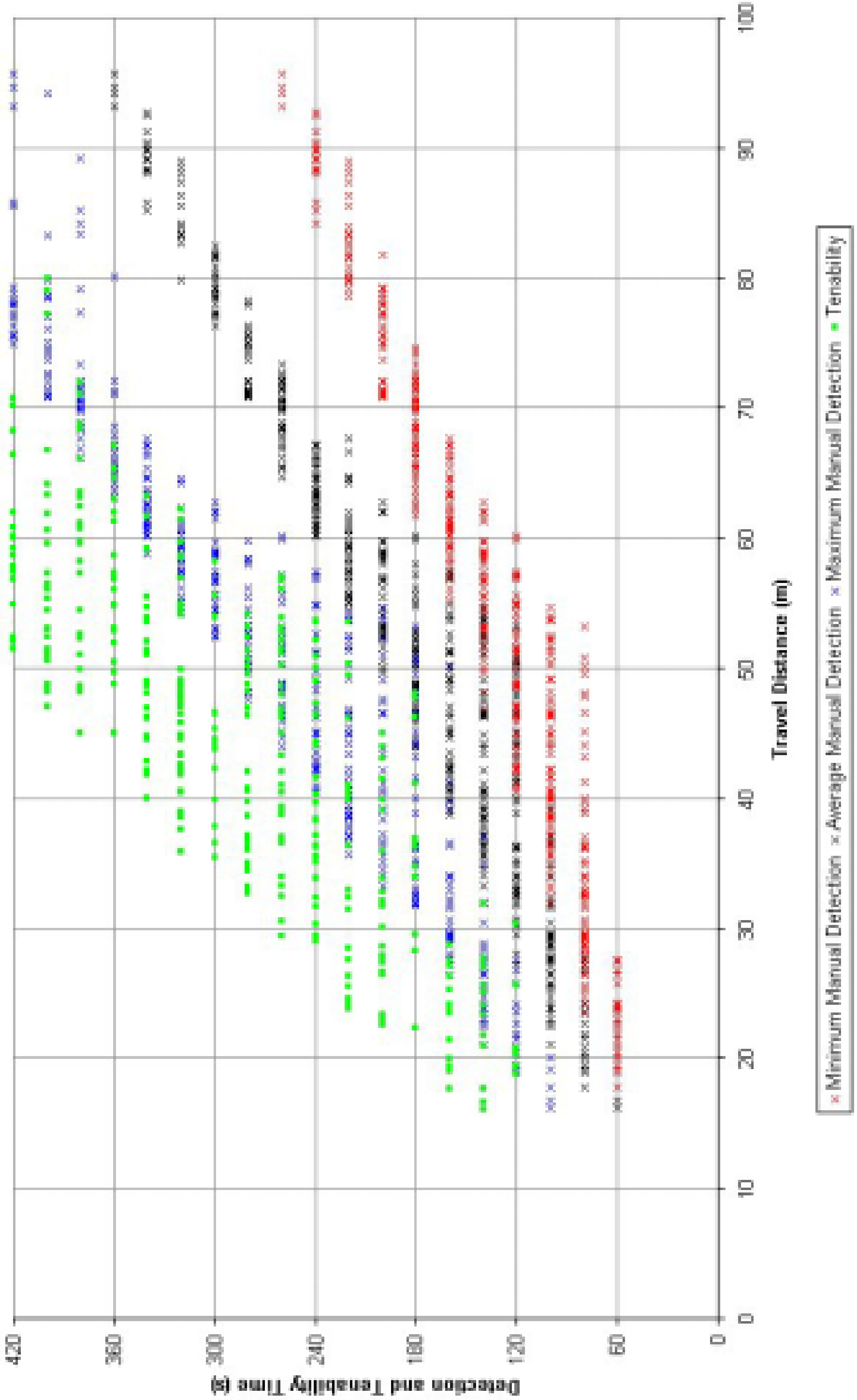

Figure 4.2 : Manual Detection Times and Tenability vs Travel Distance for Medium Fire Growth Rate

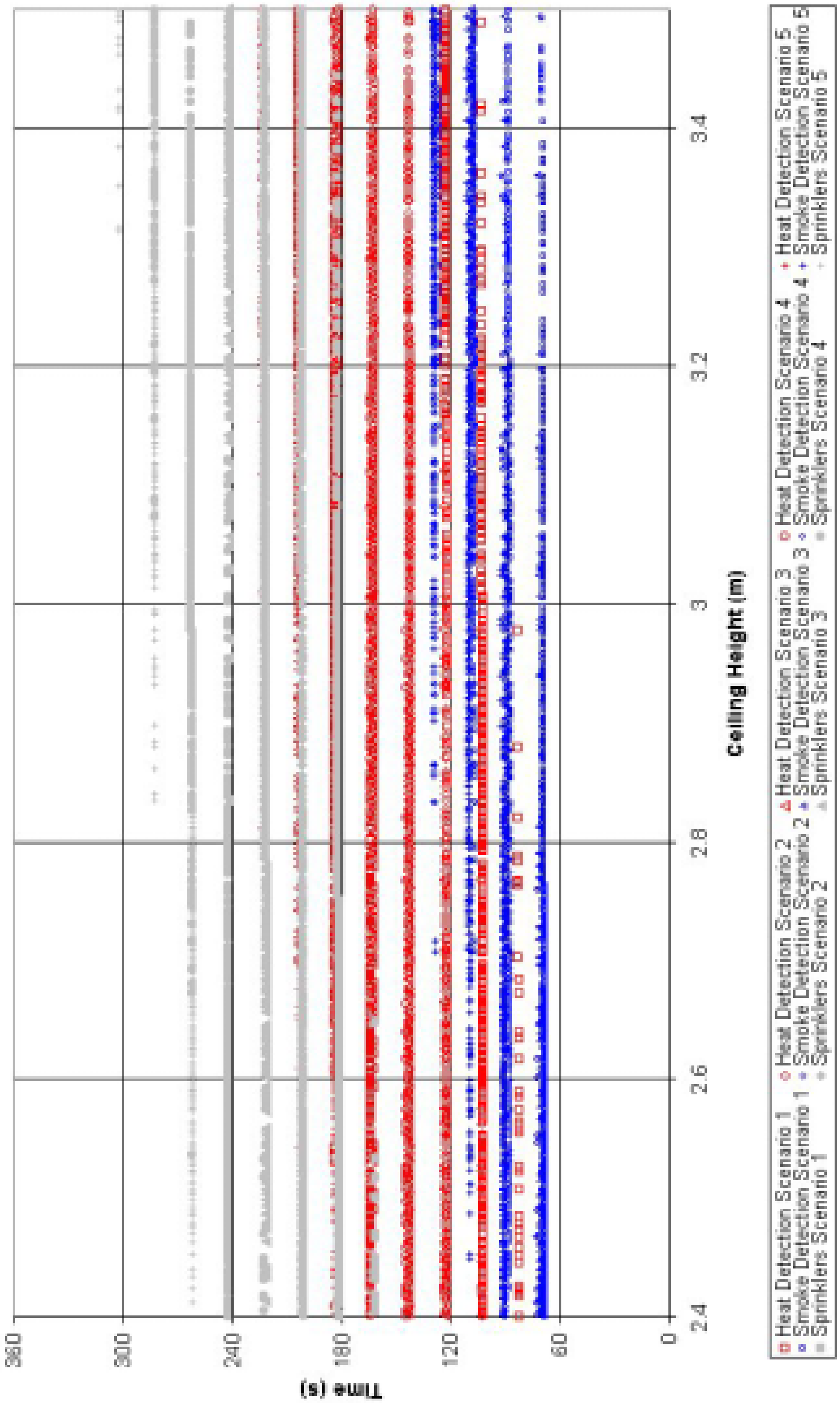

Figure 4.3 : Automatic Detector and Sprinkler Operation vs Ceiling Height for Medium Fire Growth Rate

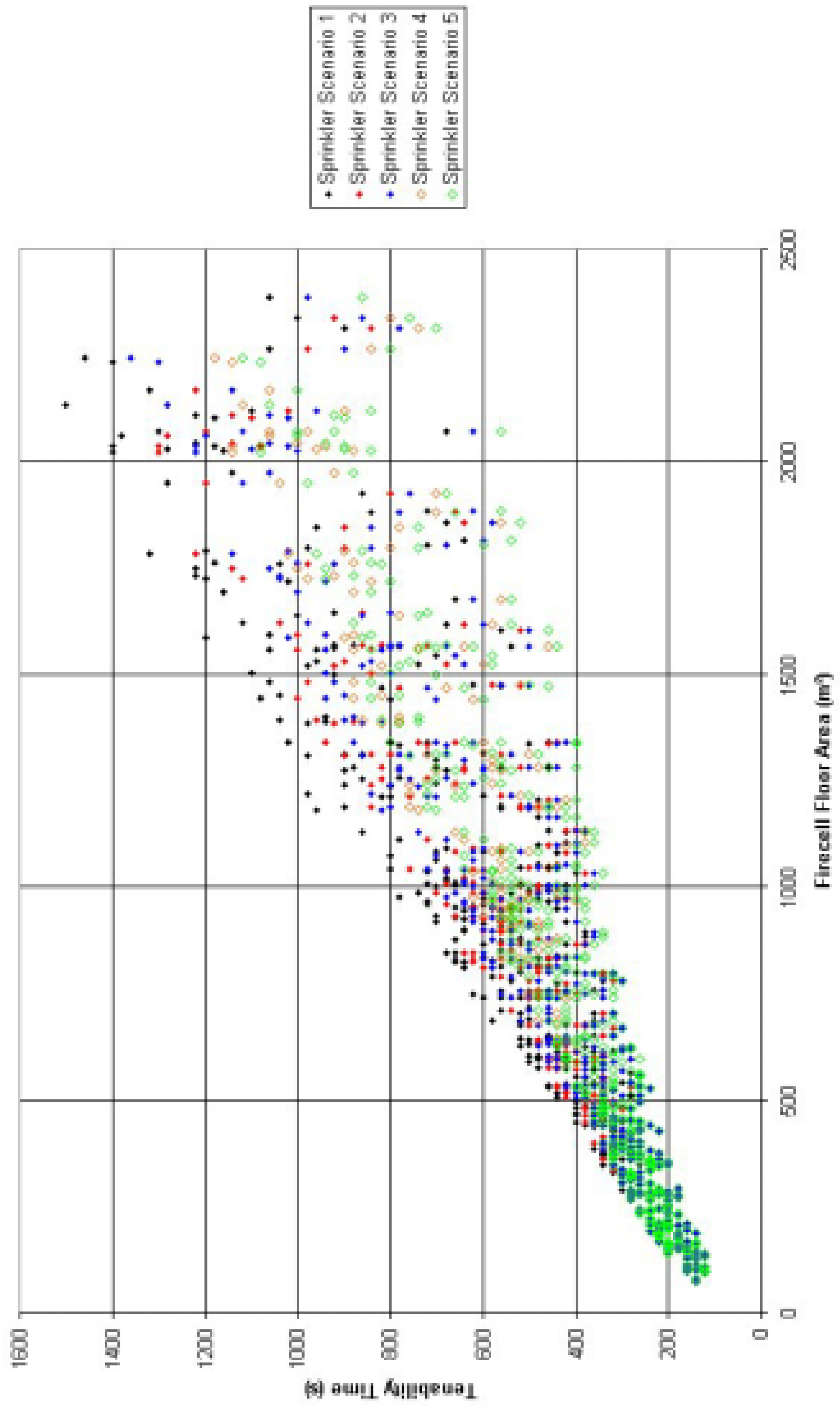

Figure 4.4 : Tenability with Sprinkler Operation vs Room Area for Medium Fire Growth Rate

4.1.2 Potential for Radiation from the Fire to Obstruct the Escape Route

The previous section addresses to the maximum time for which the firecell remains tenable, and its relationship to the room size. However, where the firecell is only provided with a single escape route, there is a risk that the fire may be in such a location that the radiation from the fire can prevent egress before tenable conditions are lost. Table 4.1 and Table 4.2 give the maximum fire sizes, and the times at which these sizes are reached for the various growth rates, that will permit egress when the fire is 1.0 m, 2.0 m, and 3.0 m from the escape route for the relevant travel speeds. The criteria here for successful egress (as described in Section 3.2.2), is that the skin temperature of the occupants does not exceed 44ºC due to radiation from the fire.

Separation	Limiting Fire Size	Slow Fire Limiting Time	Medium Fire Limiting Time	Fast Fire Limiting Time	Ultra-Fast Fire Limiting Time
1.0 m	536 kW	439 sec	219 sec	110 sec	55 sec
2.0 m	1607 kW	760 sec	380 sec	190 sec	95 sec
3.0 m	3069 kW	1051 sec	526 sec	263 sec	131 sec

Table 4.1 : Radiation and Separation - 1.2 m/s Travel Speed in Working Environment

Separation	Limiting Fire Size	Slow Fire Limiting Time	Medium Fire Limiting Time	Fast Fire Limiting Time	Ultra-Fast Fire Limiting Time
1.0 m	295 kW	326 sec	163 sec	81 sec	41 sec
2.0 m	1031 kW	609 sec	305 sec	152 sec	76 sec
3.0 m	2173 kW	887 sec	442 sec	221 sec	111 sec

Table 4.2 : Radiation and Separation - 0.8 m/s Travel Speed in Crowd Environment

The effect of these constrictions of the tenability time are shown in Figure 4.5, Figure 4.6, Figure 4.7, and Figure 4.8 for the different fire growth rates.

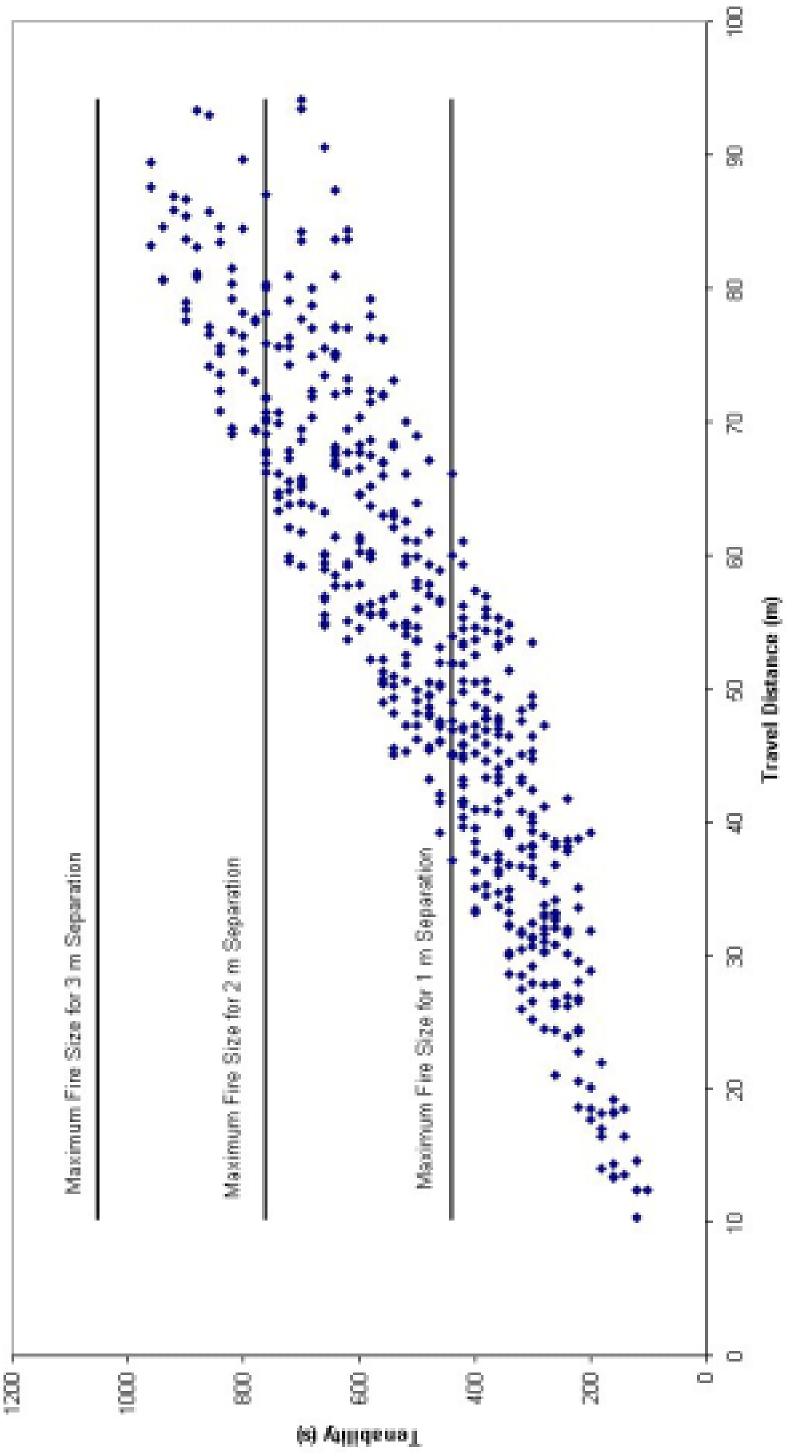

Figure 4.5 : Tenability Time for Slow Fire Growth Rate

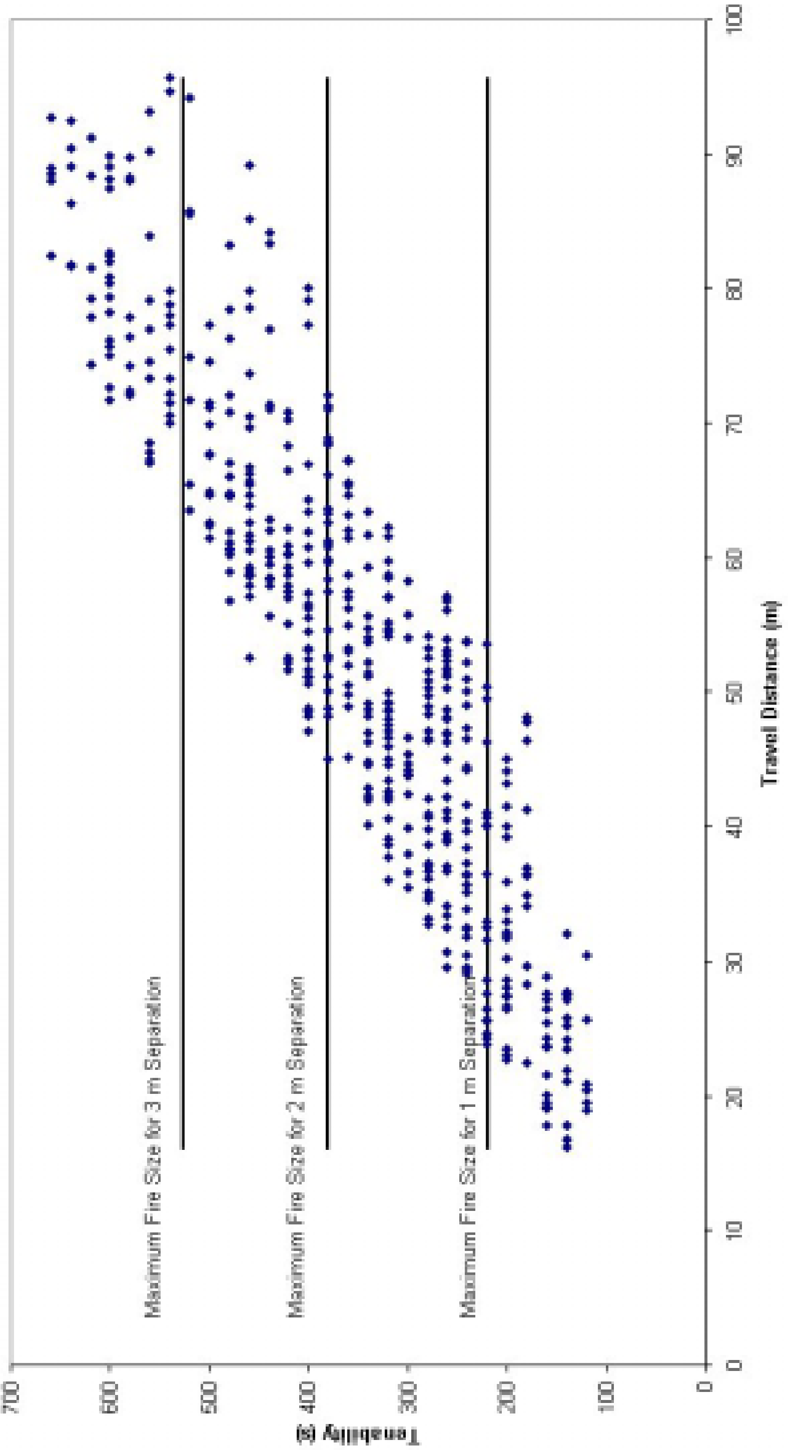

Figure 4.6 : Tenability Time for Medium Fire Growth Rate

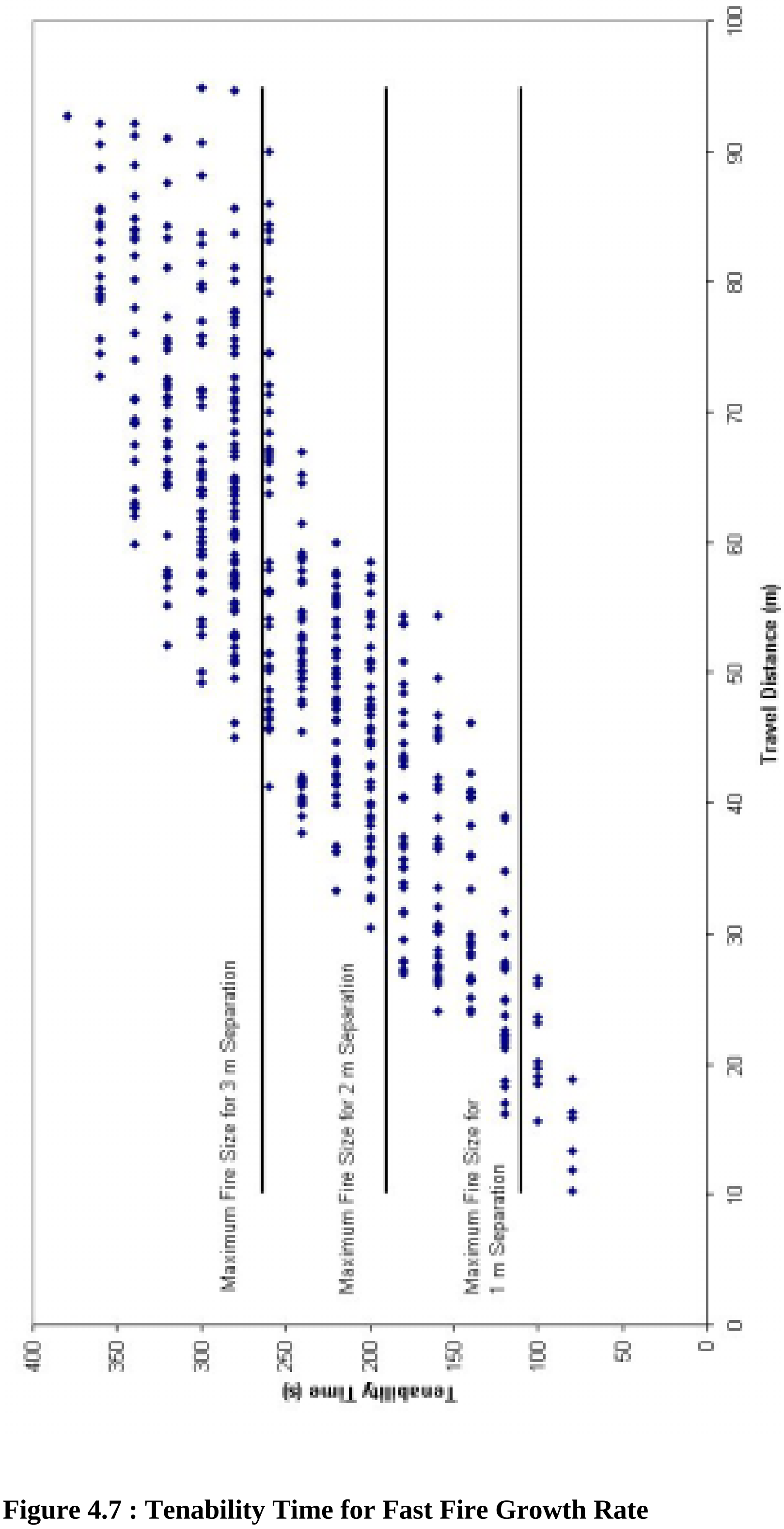

Figure 4.7 : Tenability Time for Fast Fire Growth Rate

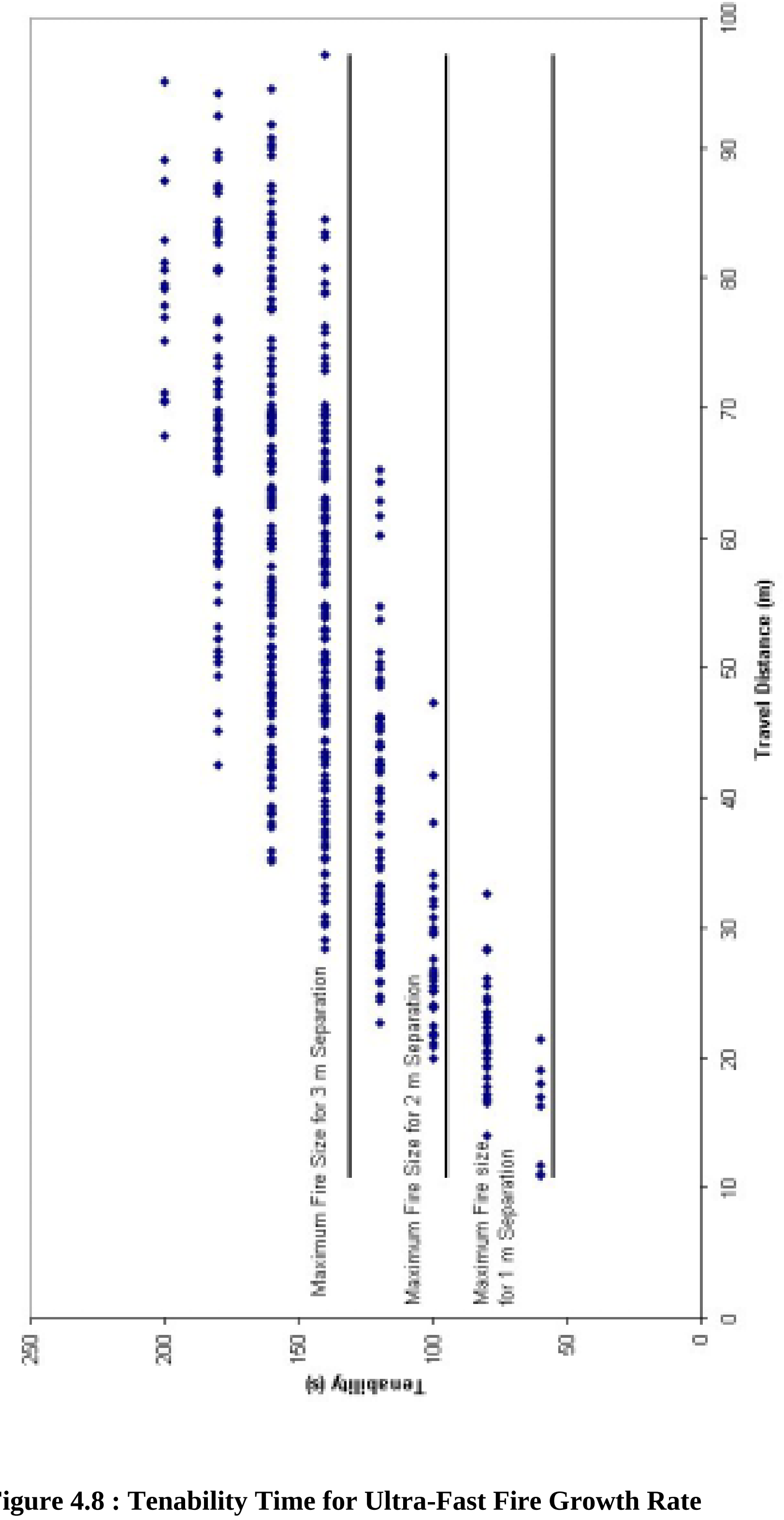

Figure 4.8 : Tenability Time for Ultra-Fast Fire Growth Rate

However, as well as the effect, the probability of a fire being in a location where it might affect egress should also be considered. In the following assessment, it is assumed that there are several possible routes through the firecell to the single escape route. Therefore, radiation from the fire will only restrict egress if it is located adjacent to this final exit point, as indicated in Figure 4.9. The size of the fire that might obstruct occupants is taken as the size of the fire when tenability in the firecell is lost, and the separation required between the exit route and a fire of that size is calculated using the trend-line equations determined in Figure 3.1.

Conservatively, the separation required is the separation between the escape route and the edge of the item. The calculation method (assuming a spherical heat flux distribution pattern), is based on radiation from the centre of the fire, but may not be totally accurate at close distances. Although crude, it is still considered sufficiently accurate for this study.

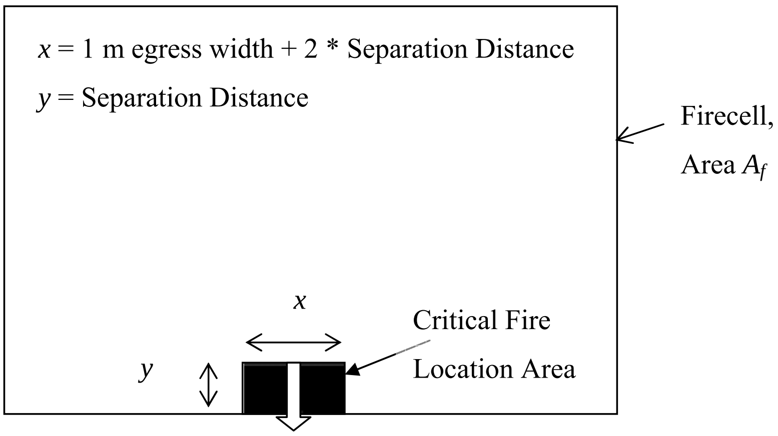

Figure 4.9 : Fire Obstruction Criteria

To illustrate the situation, consider a medium growth rate fire in the firecell. At the time that tenability is reached, the fire will have reached a certain size. The radiation from a fire this size will prevent occupants passing within a separation distance, y of the edge of the item on fire. Therefore, the critical fire location area (indicated in the figure above) can be determined for each fire scenario, and the ratio of this area to the remainder of the firecell is defined here as the probability of the fire obstructing egress (as given in Equation 4.2).

$$P_{obstruction} = \frac{x \cdot y}{Area}$$ Equation 4.2

A further modification is also made to this probability of obstruction, in which the probability of a fire occurring per square metre is no greater in a small firecell than in a large firecell. This is referred to here as the normalised probability of obstruction. This is calculated as shown in Equation 4.3, where A_{max} is the area of the largest firecell in the analysis.

$$P_{normalised} \frac{x \cdot y}{Area}\left(\frac{Area}{A_{\max}}\right)$$ Equation 4.3

These probabilities are graphed in Figure 4.10 and Figure 4.11. In Figure 4.10, it can be seen that where the probability is not normalised, the probability of obstruction increases in an exponential fashion as the firecell size reduces. This is due to the small area of the firecell in relation to the area where a fire might obstruct egress. When the probability is normalised, the probability of fire occurring in a small firecell is less due to the lesser area of the firecell. In a small firecell, where tenability conditions are lost earlier (due to the small smoke storage volume), the fire size at loss of tenability is smaller, and hence the influence of radiation from the fire is smaller. This then explains the reduction in normalised probability of a fire controlling egress from smaller firecells.

In the situations where sprinklers are provided, note that the normalised probability is significantly less than when sprinklers are not installed (typically 0.3% in comparison to 1-2% when sprinklers not provided). This is due to the sprinkler operation controlling the fire size, and reducing the critical area. The size of the fire is dependent on the time at which the sprinkler operates which is independent of the room size hence there is no reduction in the normalised probability in small firecells. Instead of separations of up to 3 m or more being required, the sprinkler operation controls the fire size such that the separation required is typically less than 1.5 m for medium fire growth rate. When the fire growth rate is faster, the fire tends to be larger and the separation increases. A fast fire still typically needs a separation of 1.6 m, and an ultra-fast fire requires an average separation of just over 2 m.

Note that the probabilities discussed above and illustrated in the graphs are not real probabilities, and do not reflect the actual probability of a fire in such a location. The values are of use in a relative sense only.

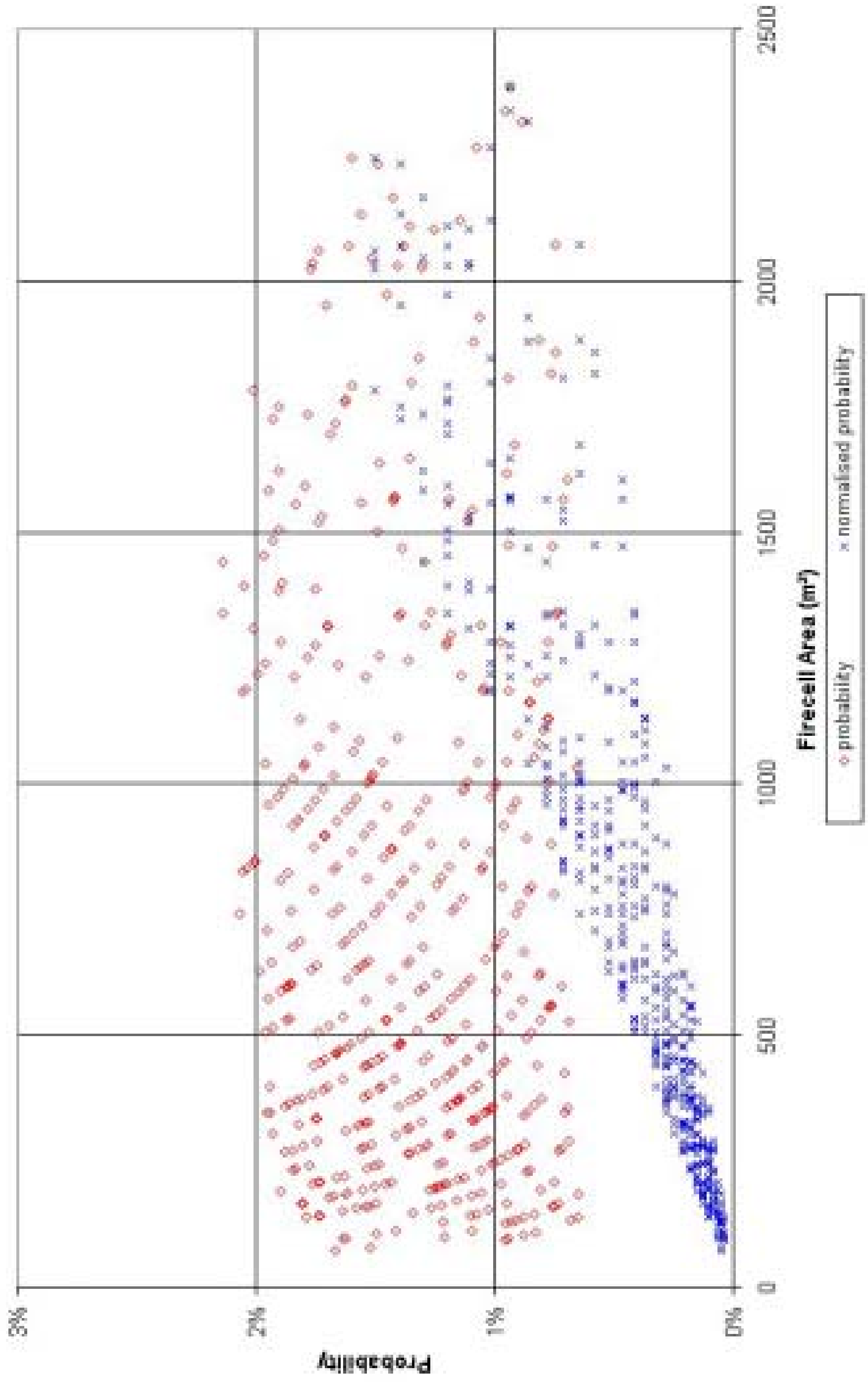

Figure 4.10 : Probability of Obstruction - Medium Fire Growth Rate

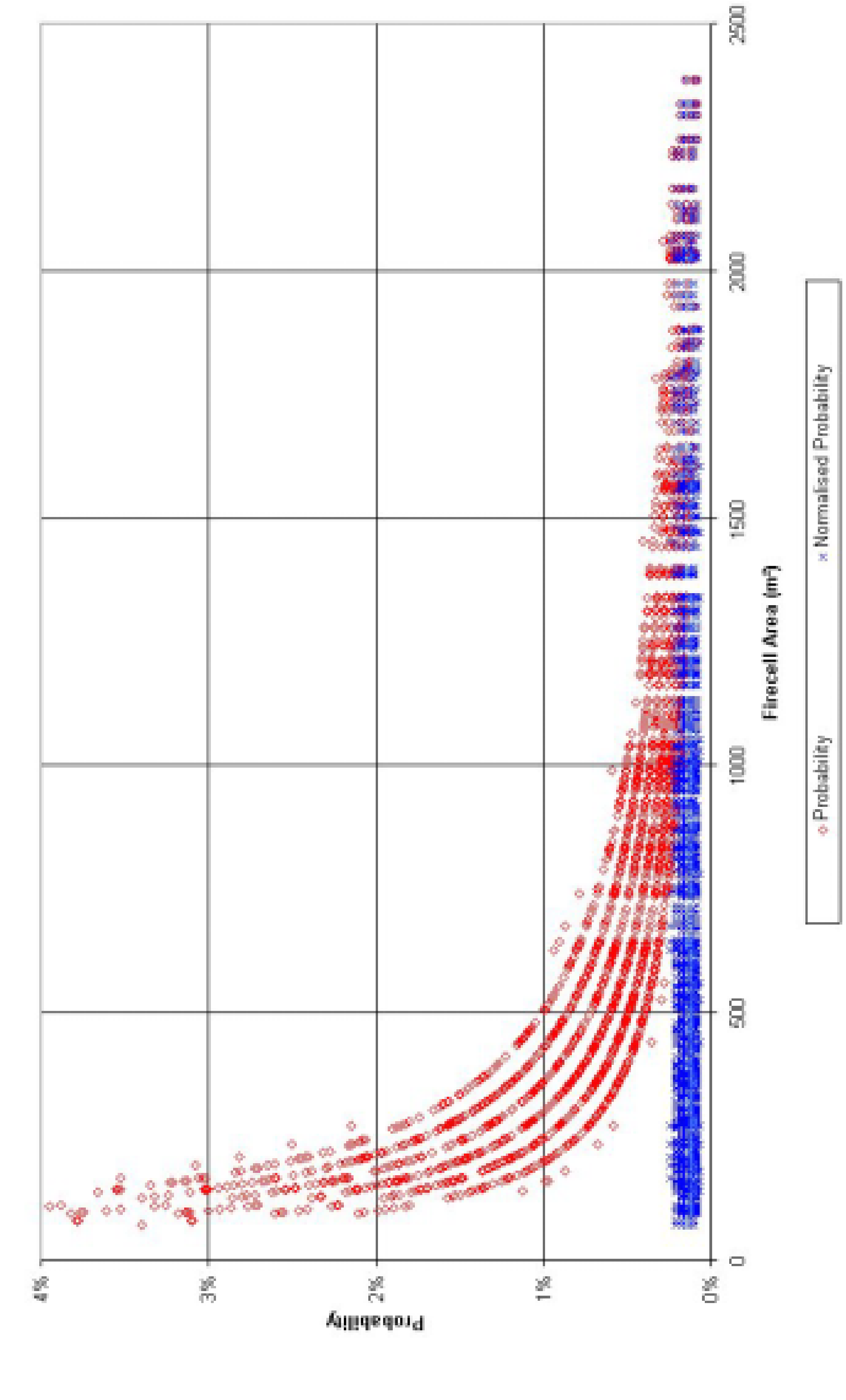

Figure 4.11 : Probability of Obstruction - Sprinkler Controlled Fire, Medium Fire Growth Rate

4.1.3 Time Available to React and Escape after Detection

As noted previously, tenability and manual detection times have a reasonably strong dependence on the firecell size, and on the longest travel distance to the final escape route from the firecell. Although automatic detectors do not have this relationship, the time available to escape after detection still retains the general dependence due to the tenability time as indicated in Figure 4.12, Figure 4.13, Figure 4.14, and Figure 4.15 for the various fire growth rates.

In these figures, the following trends can be seen:

- As the firecell size increases, the time available after manual detection for egress past fires close to the escape route decreases. This reflects the dependence of manual detection on the thickness of the smoke layer, which is in turn dependent on the firecell size.

- Available time after automatic detector operation is typically fairly constant where radiation may control egress. This is because neither the detection nor the radiation from the fire are related to the firecell size.

- The available time after automatic detector operation increases with firecell size where only tenability of the firecell affects the success of egress. Although the detector operation is not dependent on firecell size, the tenability time is related to it, hence the continuing relationship.

- In smaller firecells, detection often occurs after tenability is lost, particularly where the maximum travel distance is less than 20 m.

The next step is to assess the impact of the varying *pre-movement* times associated with the different *occupancies* on the time remaining for egress movement. Firstly, Table 4.3 gives the *pre-movement* times used in this analysis. It is apparent on inspection that these will not leave any travel time for egress in many situations, particularly where the fire growth rate is faster than a medium fire. Further, this seems to show that detection may occur even after loss of tenability, particularly in small firecells. This is where the manual detection model used is clearly inadequate.

Occupant Type	Average Pre-movement time			Minimum Pre-movement time (after delayed manual detection)			Maximum Pre-movement time (after early manual detection)		
	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min
Office	86	135	39	71	111	32	109	171	50
Retail	107	138	49	80	126	36	160	251	73
Bar	130	204	59	92	145	42	218	343	99

Table 4.3 : Pre-Movement Times

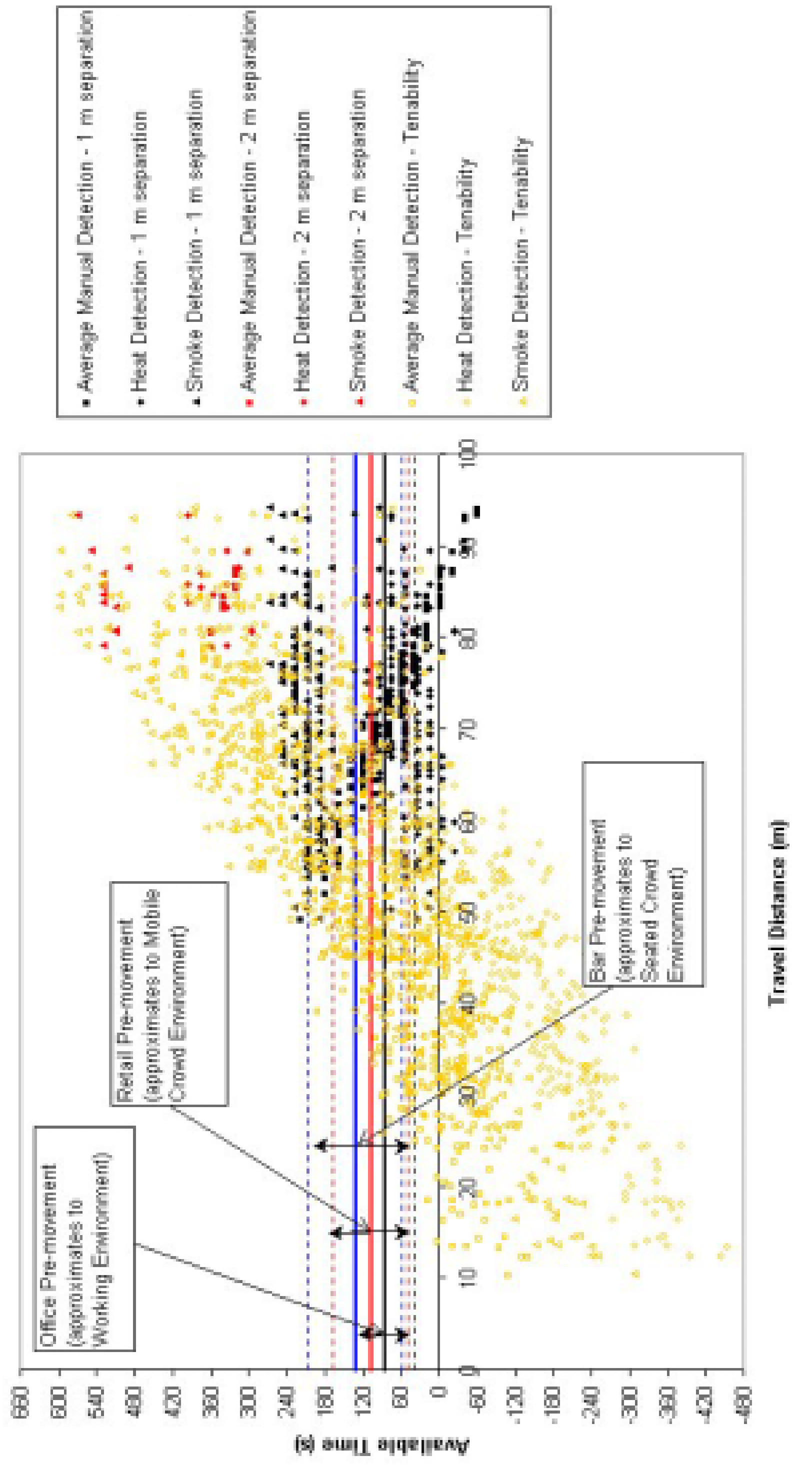

Figure 4.12 : Available Evacuation Time – Slow Fire Growth Rate

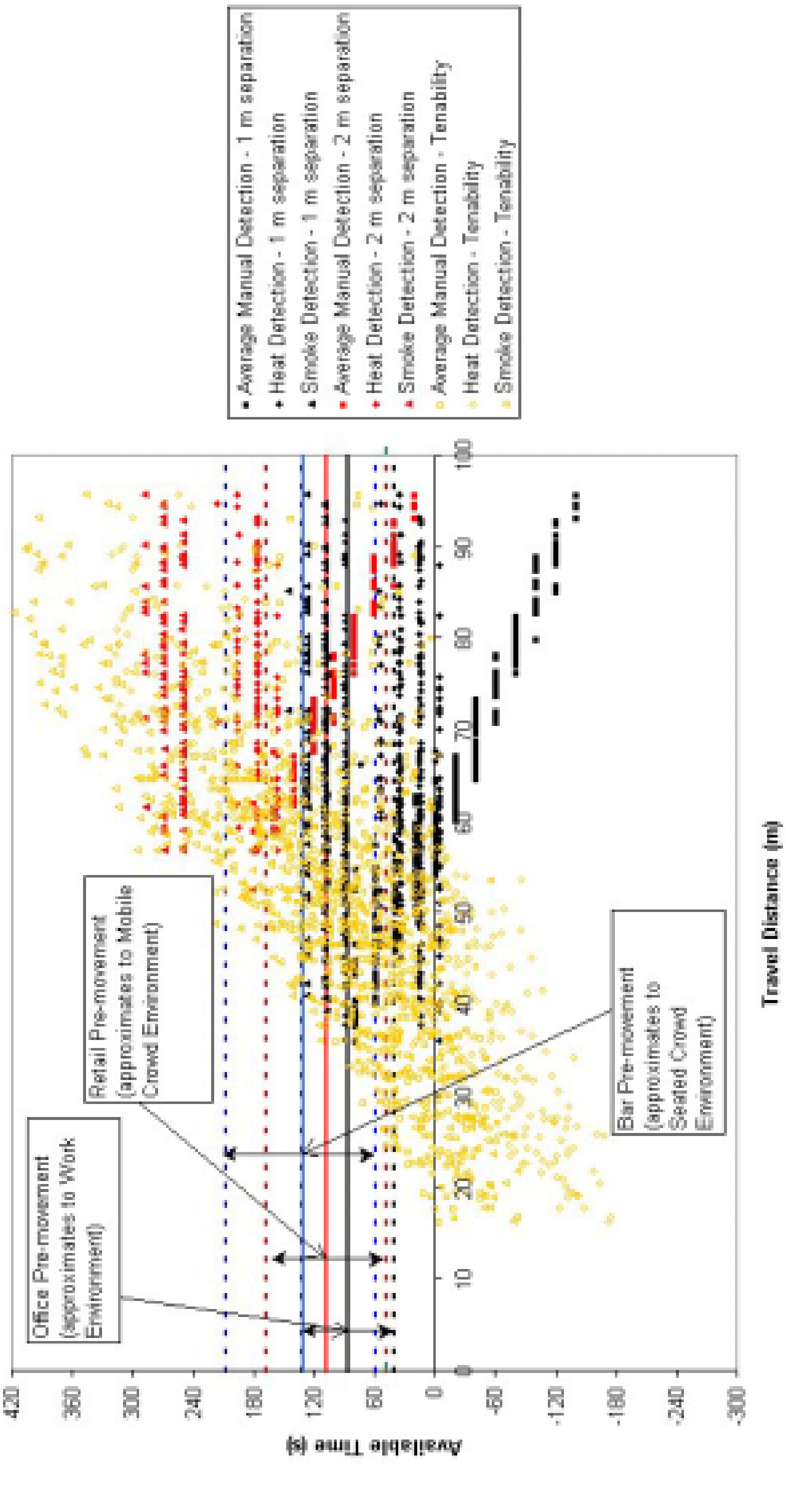

Figure 4.13 : Available Evacuation Time – Medium Fire Growth Rate

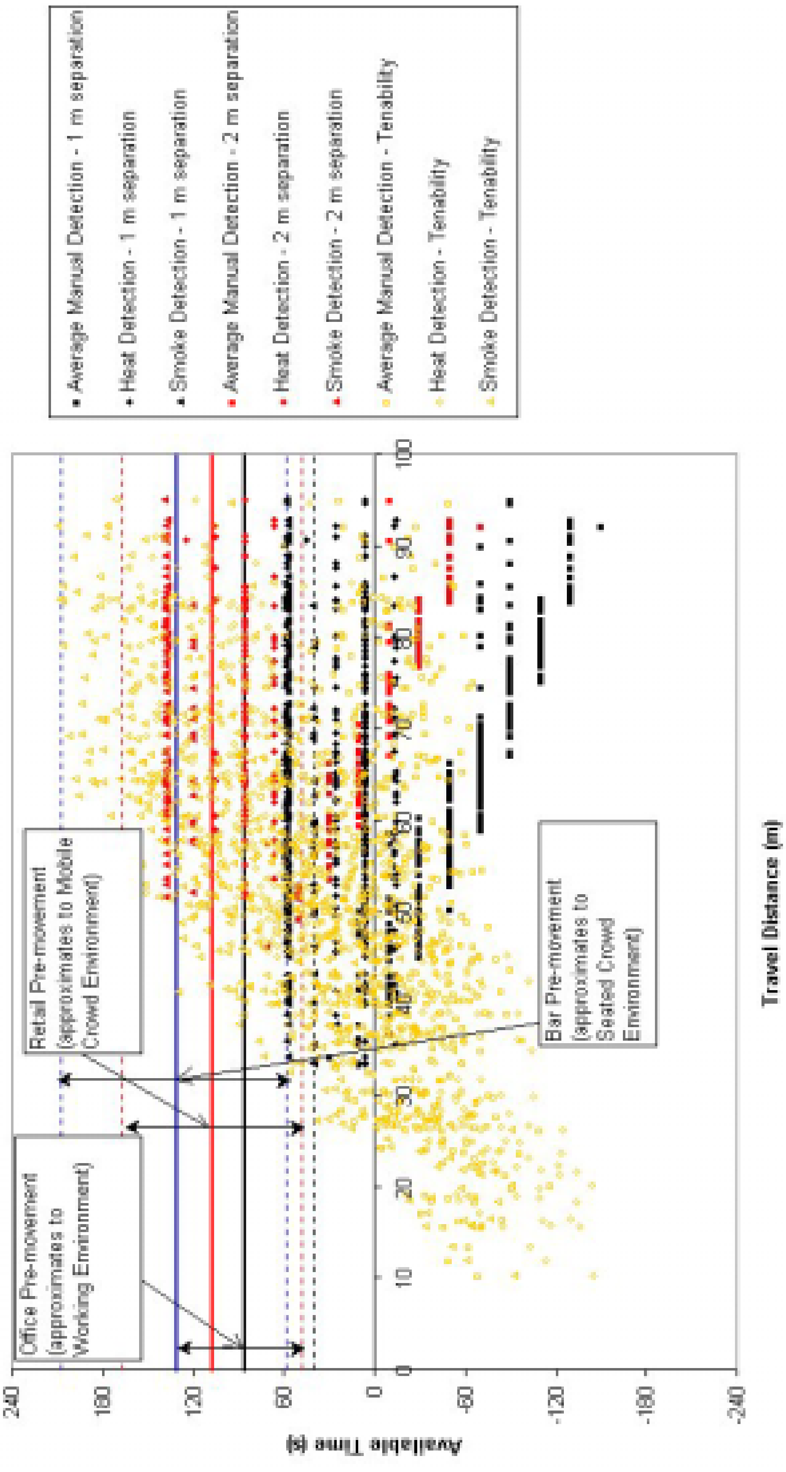

Figure 4.14 : Available Evacuation Time – Fast Fire Growth Rate

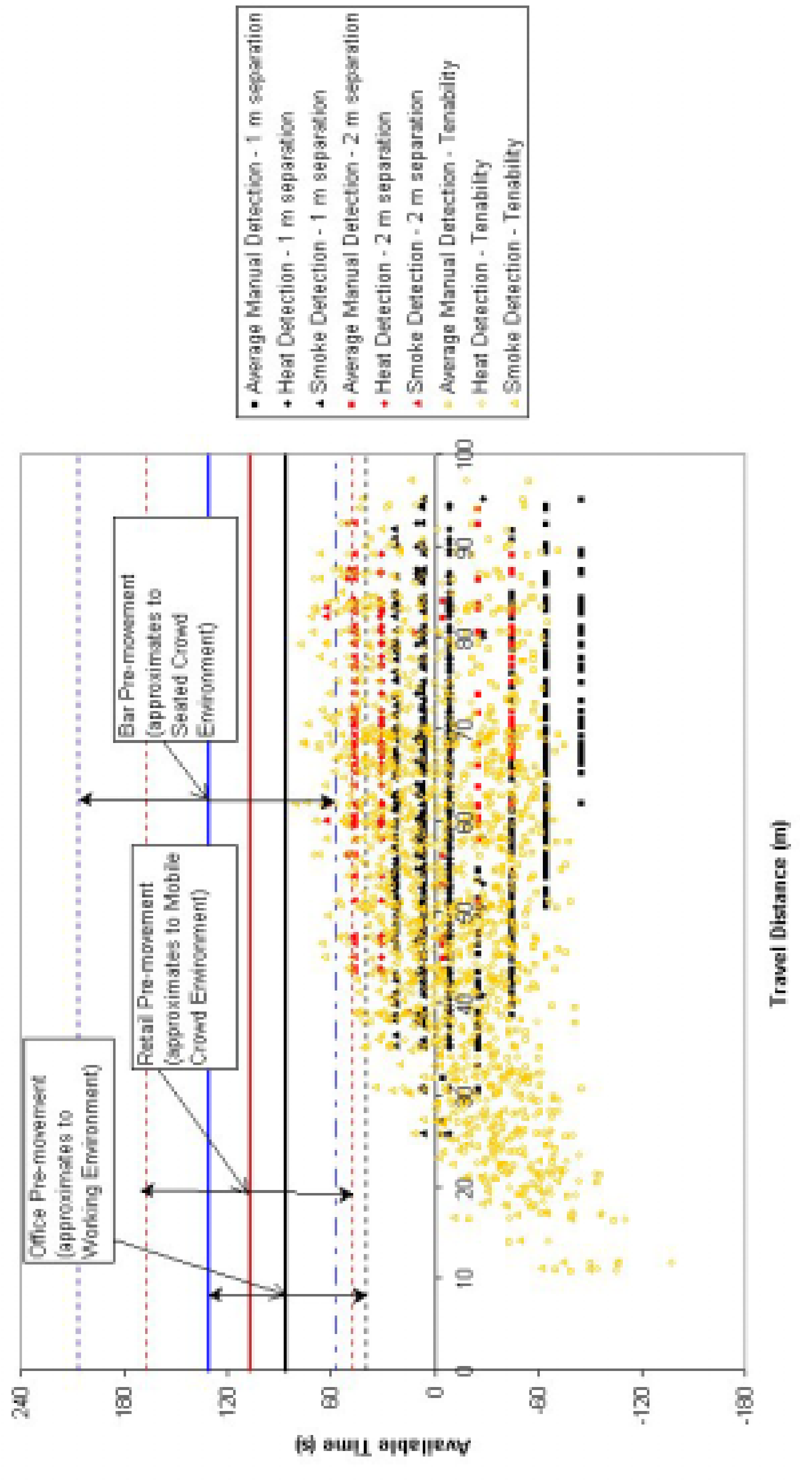

Figure 4.15 : Available Evacuation Time – Ultra-Fast Fire Growth Rate

4.1.4 Time Available for Escape

In the following sections, the effect of different fire growth rates and responses by the occupants in different *occupancies* on the successful rate of evacuation is to be assessed. Firstly, a medium fire growth rate will be evaluated for each *occupancy*, then the effects of different fire growth rates on those results will be investigated. An adequate or satisfactory success rate is defined here as when the evacuation outcome success rate exceeds 90% for that scenario.

<u>Work Environment - Office</u>

Given the clear relationship between travel distance and time between detection and tenability for most, if not all detection methods, it is reasonable to assume that this relationship will continue to apply to the time available for escape (ie after *pre-movement* activities have been undertaken). This is shown in Figure 4.16, including a line giving the required escape time to cover the travel distance at 1.2 m/s.

To aid the evaluation of the office evacuation scenarios, refer to Figure 4.17 showing the number of scenarios with successful and unsuccessful evacuations.

When reviewing the scenario comparison graphs, note that all are similarly arranged. The sequence of bars from left to right first shows the scenarios where the fire is 1 m from the escape route. The second series gives the results for a 2 m separation, the third series, a 3 m separation, and the fourth series gives the results where the fire is remote from the escape route.

These figures give the percentage of successful outcomes, being those points above the line showing required egress time – for Figure 4.17 this is from Figure 4.16. From this, an assessment of the effectiveness of the various detection methods can be made. The following comments relate to this graph.

In small firecells (with travel distance of less than 10 m), evacuation is generally predicted to be unsuccessful due to the small smoke storage volume. However, this is not considered totally reasonable as the scenarios include a *pre-movement* time of between 40 and 132 seconds. In a small firecell, occupants will tend to be in close proximity to the fire, and hence more aware of cues other than smoke. The travel distances and hence travel times are also relatively small. In such a situation it does not seem reasonable for manual detection, or even *pre-movement* activities to continue after tenability is lost, and it is most likely that these occupants would quickly recognise the situation, and the danger from the smoke. However, it should also be noted that the travel time assumed in these analyses does not include flow time through doors (this being more dependent on the number of people). Where this time is long in comparison to the travel time to reach the doors, it would be reasonable to assume that this time is incorporated in the *pre-movement* time, which might otherwise be shorter than predicted due to greater occupant awareness of the fire.

In slightly larger firecells, where the travel distance for egress is between 10 and 20 m, manual detection consistently occurs before automatic detectors operate. Although a reasonable proportion of outcomes dependent on manual detection do not have sufficient time for egress, few of those dependent on automatic detection are successful.

As the firecell size increases, manual detection times increase, although automatic detection times do not. While smoke detectors give increasingly earlier warning than manual detection (resulting in the greatest number of successful escape outcomes), heat detectors do not out-perform the occupants as detectors until the firecell size is such that the travel distances exceed 60 m.

As could be implied from Figure 4.17, there is little difference in the success rate of evacuation once the separation between the fire and the escape route exceeds 2 m. In the largest firecells where the travel distance is greater than 60 m, manual detection tends to be inadequate to permit egress within 2 m of the fire. A separation of 1 m usually results in failure, although there are a small number of successful outcomes occurring when the travel distance is less than 30 m, and either occupant detection or smoke detection provides the warning.

Next, look at the variation between the scenarios for the different detection methods. These are shown in Figure 4.18, Figure 4.19, and Figure 4.20.

The different manual detection scenarios are dependent on the alertness of the occupants, and not readily prescribable (unlike automatic detectors where the response and spacing determine the detection response time), these scenarios illustrate the range of possible successful evacuations. As noted before, there appears to be little chance of success in small firecells, but this is not considered realistic for the reasons given above. In larger firecells, the success rate improves with travel distance, and it appears that the distance of the fire from the escape route has little effect on the success rate. However, where the fire is 1 m or closer , there is little chance of success. Where the occupants are not particularly observant, manual detection is typically inadequate. However, in the cases where they are more observant, reacting at the average time, more outcomes are successful than unsuccessful.

The different heat detection scenarios have been created (as noted in Section 3), by changing the spacing of the detectors. Figure 4.19 shows that this has a significant effect on the success rate of the evacuations. All spacings are compliant with the requirements of NZS 4512, and the spacing scenario illustrated in Figure 4.17 is the largest spacing, ie Scenario 5. It can be seen that the separation of the fire from the escape route has little effect on the success rate provided it is greater than 1 m, even over long travel distances. Successful evacuation is therefore typically controlled by the tenability of the firecell rather than radiation to the escape route.

As with the heat detection scenarios, the smoke detection scenarios are also for different detector spacings, and Figure 4.20 indicates that these too have a significant effect on the chance of a successful evacuation. A comparison of Figure 4.19 and Figure 4.20 indicates that scenario 1 of the heat detectors (2 m spacing) is similar in success to scenario 5 of the smoke detectors (10 m spacing). The similarity in activation times is also apparent in Figure 4.3. Successful egress is usually possible where the travel distance is greater than 30 m and the fire is 2 m or more from the escape route.

Finally, consider the effect of sprinklers. In Figure 4.21, the available escape time from a sprinklered office is shown. Manual detection, detection by sprinkler activation, and detection by smoke detector activation is considered. Note that the required separation of the fire from the egress route is not included in the assessment as it is usually less than 1.5 m. The graph indicates that the available escape time usually exceeds the required escape time in most situations, although in smaller firecells, tenability time still tends to be too short. Figure 4.22 confirms this, but also indicates that in these situations, manual detection and, where provided, smoke detection, is most likely to provide adequate alert. The benefits of smoke detection are most apparent in the larger firecells, ie travel distance of 40 m or more. The least satisfactory situation is when the alarm is given only by sprinkler operation. However, successful evacuation from the firecell is only relevant when people are present, and it appears to be most likely that those people would detect the fire in adequate time to permit escape.

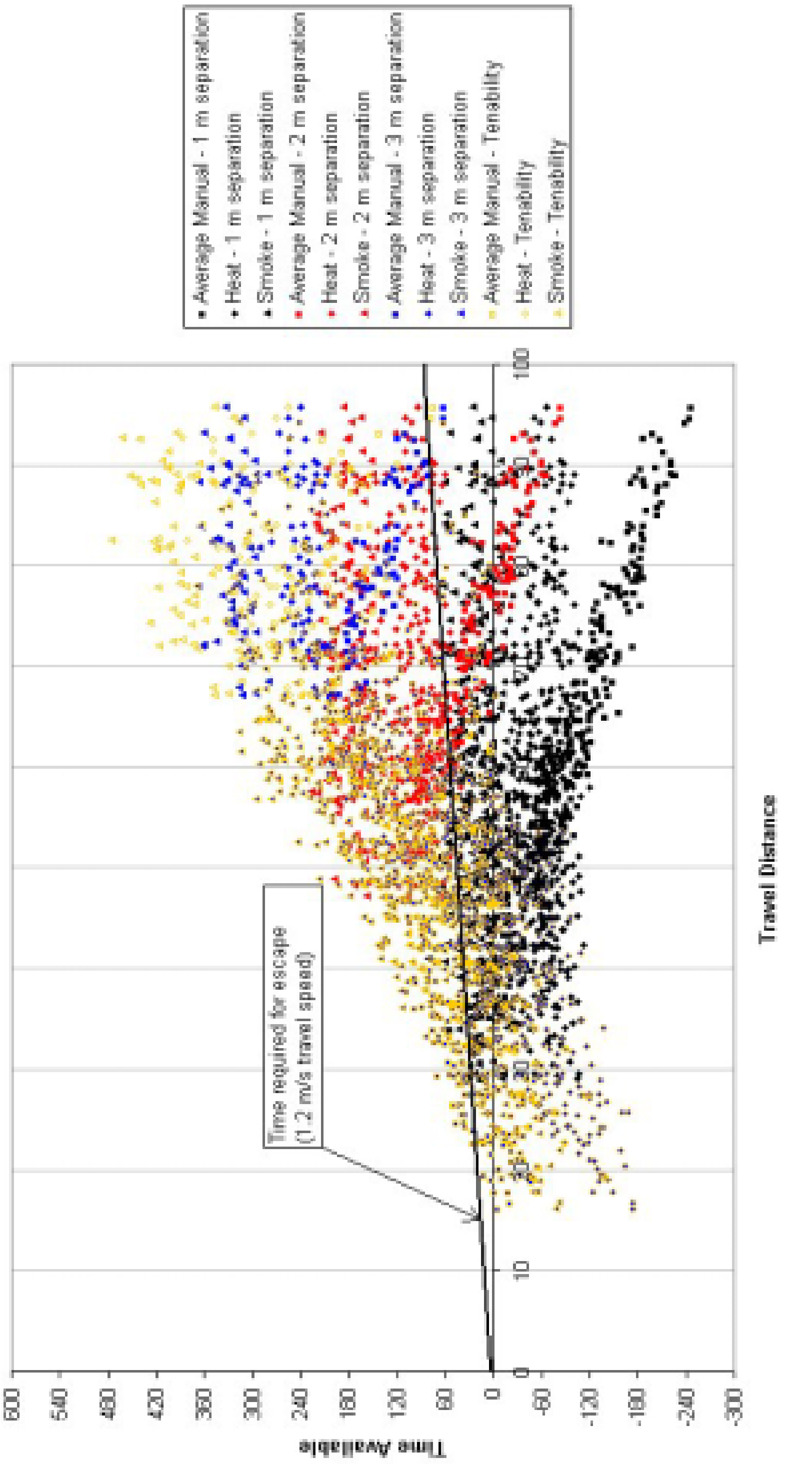

Figure 4.16 : Escape Time from Work Environment – Medium Fire Growth Rate

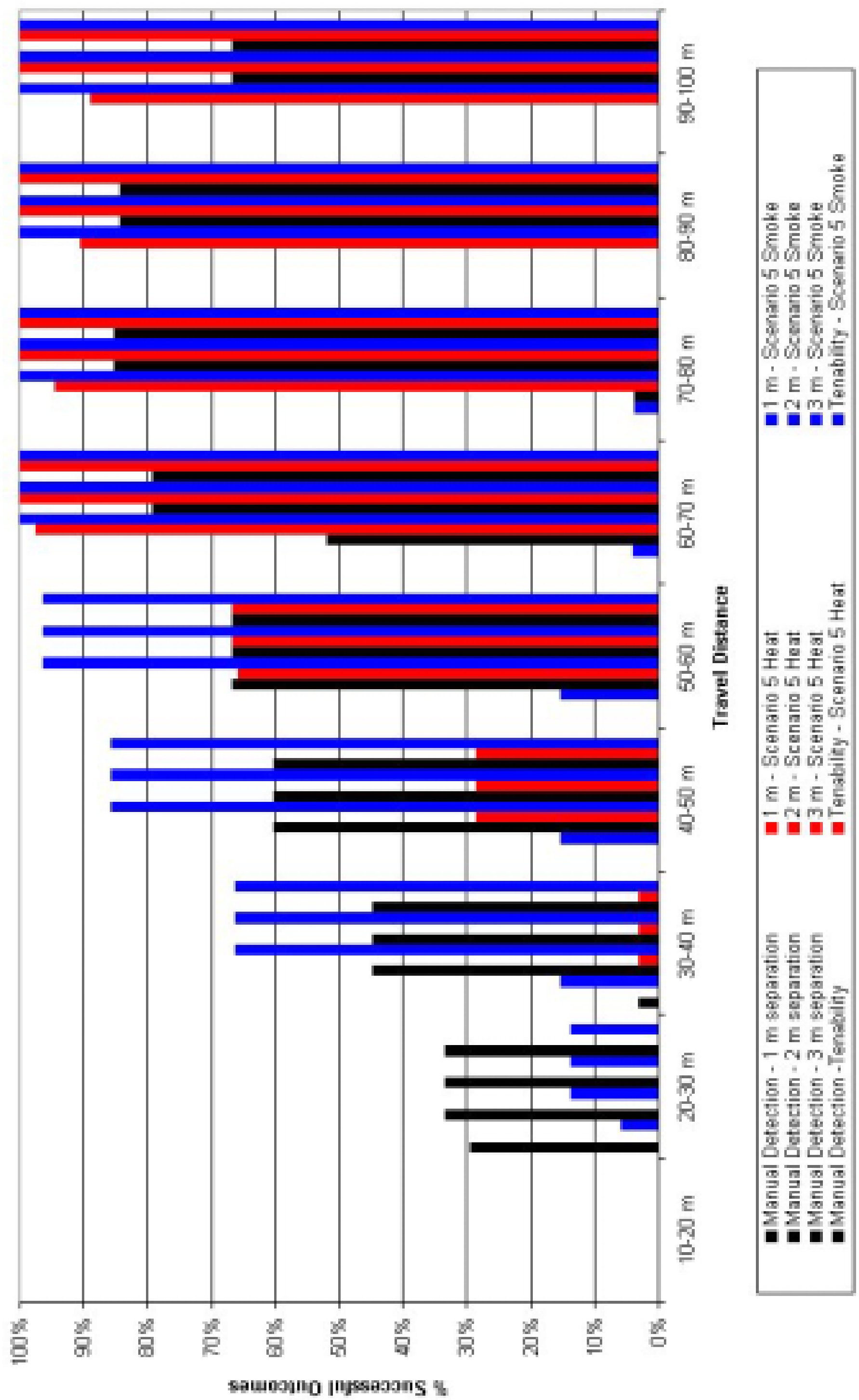

Figure 4.17 : Work Environment Escape Scenario Outcome Comparison – Medium Fire Growth Rate

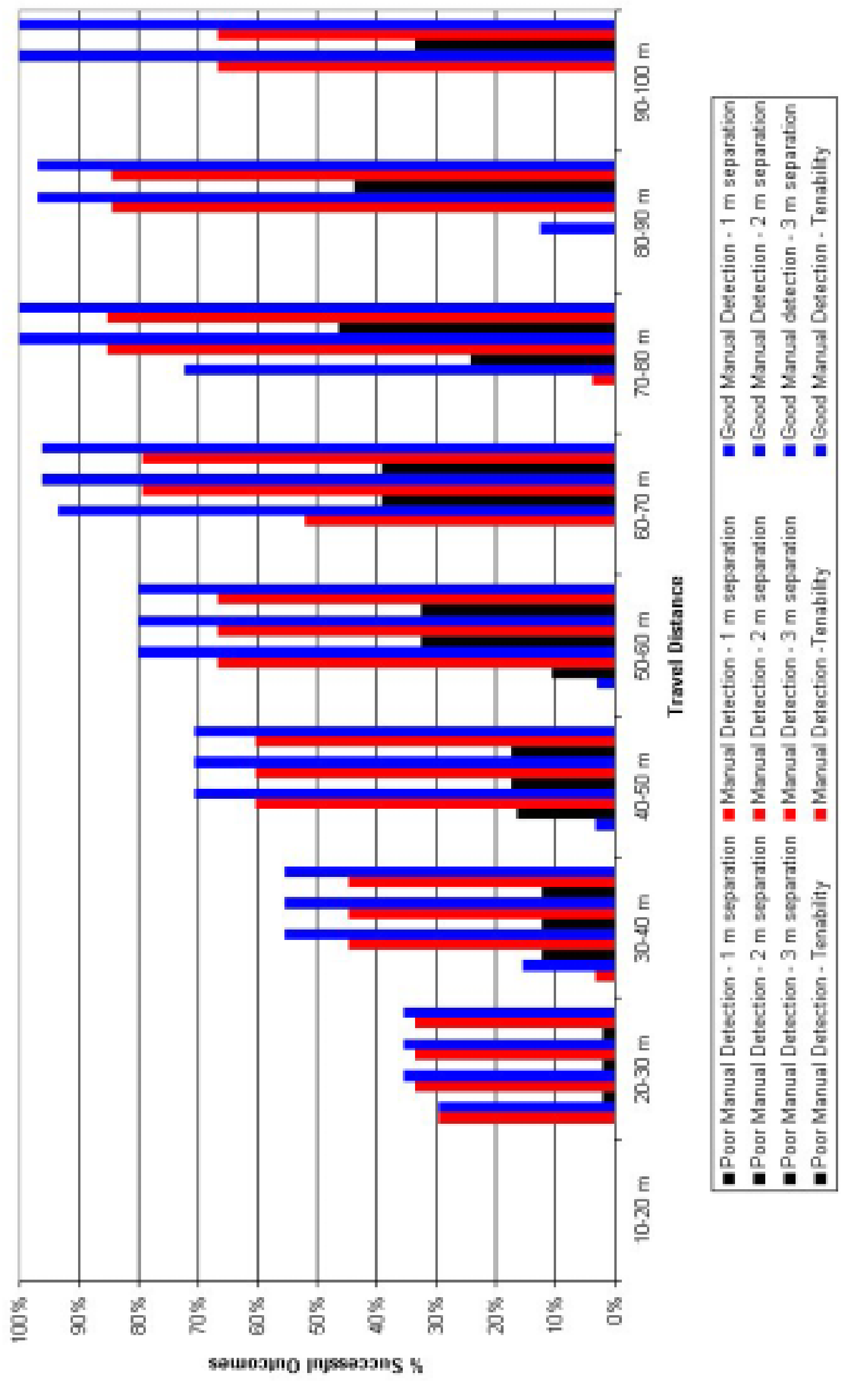

Figure 4.18 : Work Environment Manual Detection Scenario Outcome Comparison – Medium Fire Growth Rate

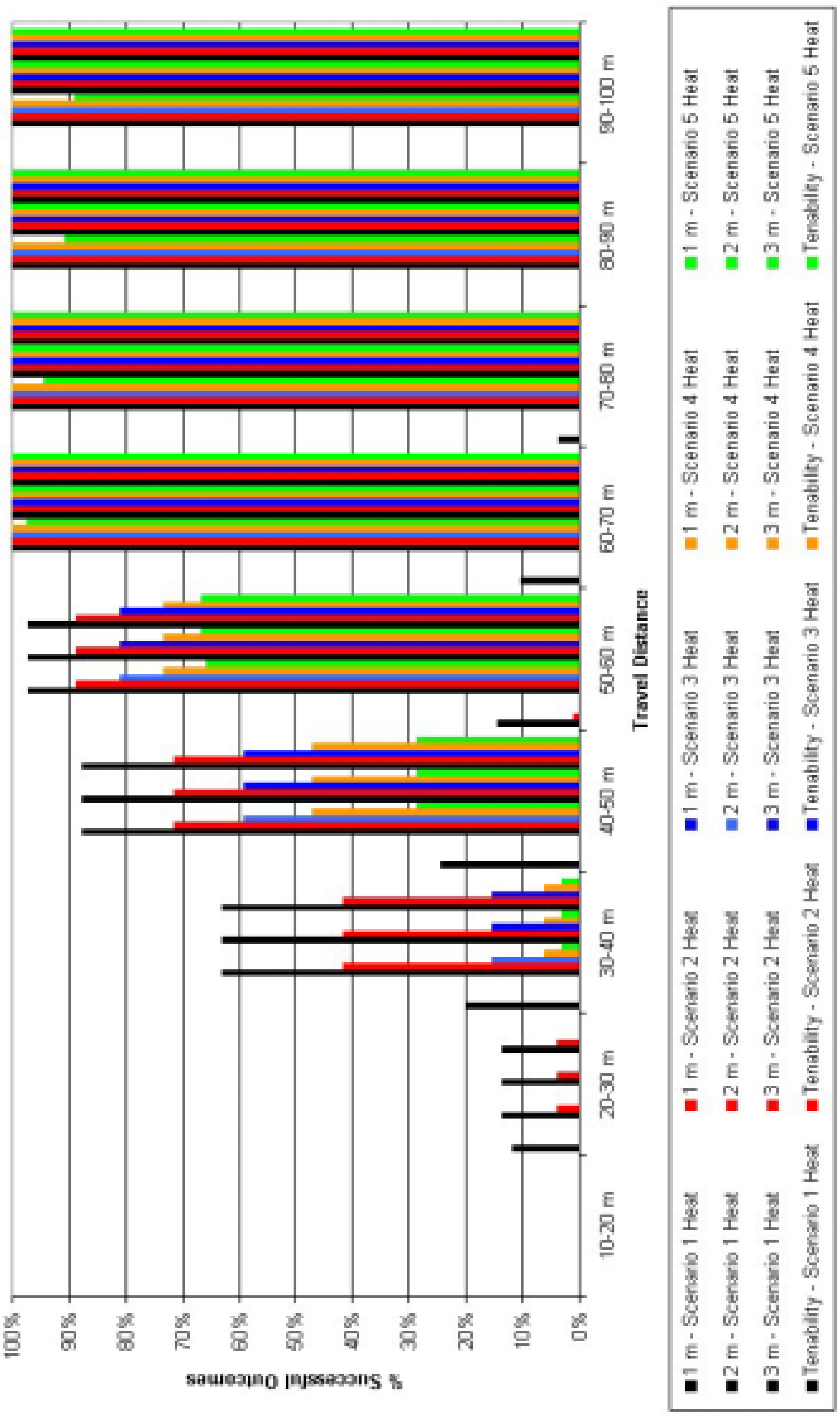

Figure 4.19 : Work Environment Escape Heat Detection Scenario Outcome Comparison – Medium Fire Growth Rate

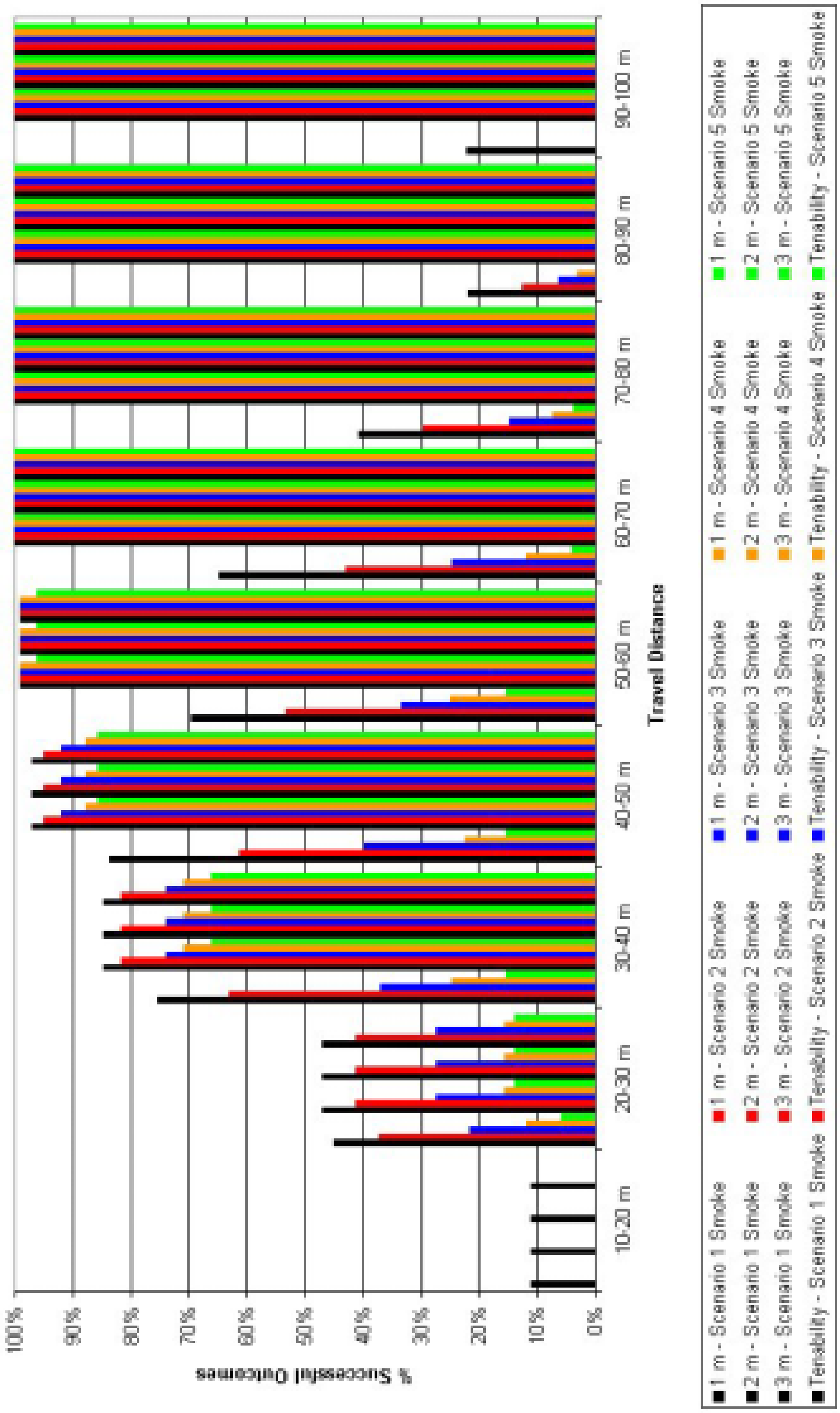

Figure 4.20 : Work Environment Escape Smoke Detection Scenario Outcome Comparison – Medium Fire Growth Rate

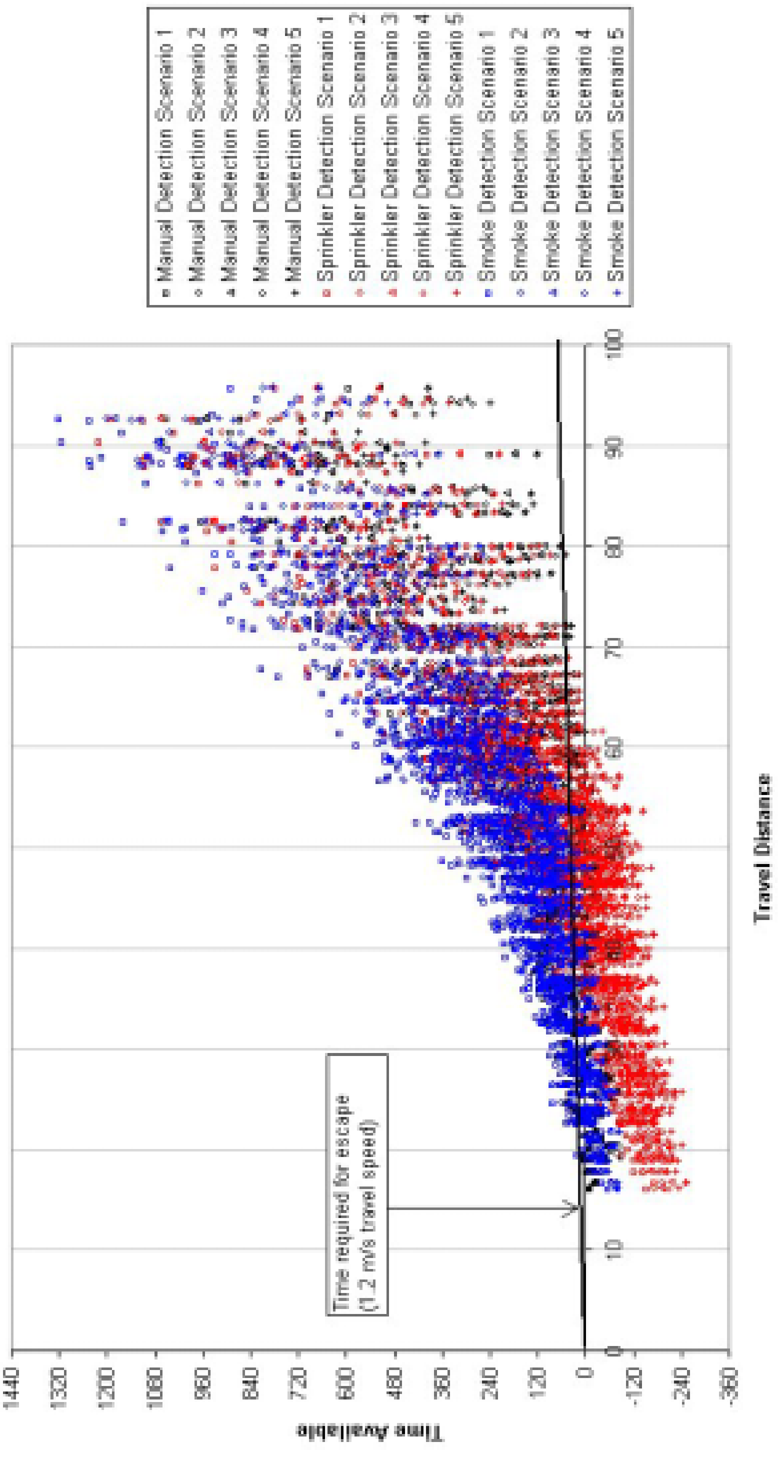

Figure 4.21 : Available Escape Time from Sprinkler Protected Work Environment – Medium Fire Growth Rate

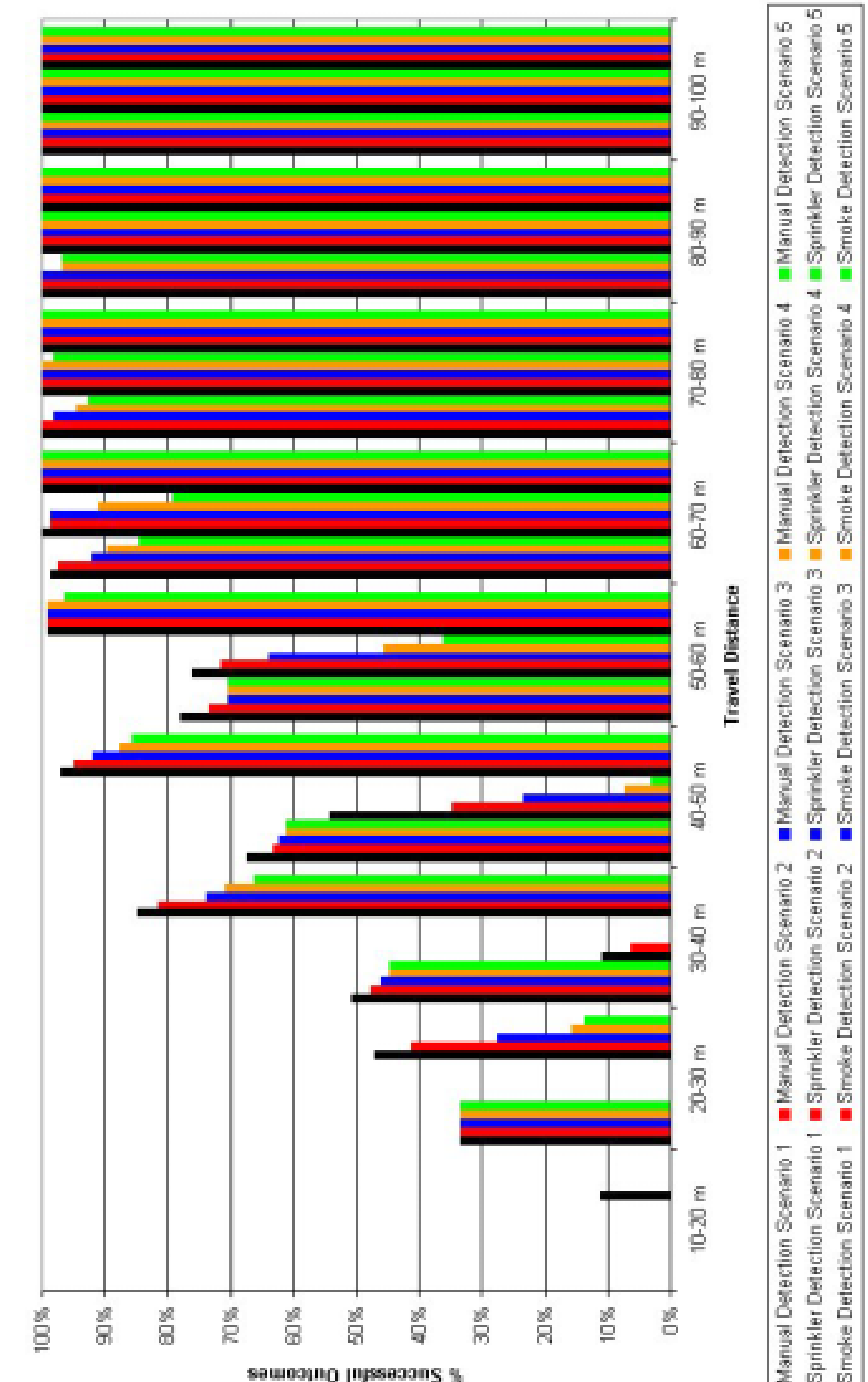

Figure 4.22 : Work Environment Escape Sprinkler Protection Scenario Outcome Comparison – Medium Fire Growth Rate

Graphs describing the results for all of the t^2 fire scenarios analysed are given in the appendices in Section 11. When these other fire growth rates are considered, the following trends can be seen:

General Comparison of Detection Methods

- Where the fire growth rate is slow and the firecell size is small, manual detection is predicted early enough to allow some successful egress outcomes.
- As the fire growth rate increases, smoke detection tends to provide increasingly earlier warning times than manual detection, and hence a greater rate of successful egress outcomes. This particularly applies to medium to large size firecells where the travel distance exceeds 30 m.
- When the fire growth rate is slow, manual and smoke detection typically occur early enough to permit egress within 1 m of the fire, although as the travel distance increases beyond 60 m, a 2 m separation is required.
- When the fire growth rate is fast, a 3 m separation is typically required, but this is not always adequate if tenability is lost first.
- Where the fire growth rate is "ultra-fast", few if any successful egress outcomes are predicted, and when they occur, are usually in response to smoke detector activation.

Manual Detection

- There continues to be a wide range of success rates for the different manual detection scenarios, and for a slow growing fire, "average" detection times are usually adequate to permit egress, even within 1 m of the fire.
- There are few successful outcomes once the fire growth rate is "fast" or "ultra-fast".

Heat Detection

- The spacing of the heat detectors continues to have a significant influence on the success rate.

- In small firecells, if heat detectors are provided at the closer spacings, adequate warning may be provided to egress past a fire no closer than 2 m to an escape route.

- As the firecell size increases, the effectiveness of the heat detector operation generally improves, and is most appropriate when the travel distance is 50 m or greater.

- If the fire has a slow growth rate the radiation is unlikely to obstruct egress when the fire is within 1 m of the escape route, and the travel distance is 50 m or less. For longer travel distances a 2 m separation is needed.

- Where the fire growth rate is fast, a 1 m separation is typically required, increasing to 2 m when the travel distance exceeds 40 m.

- Where the fire growth rate is ultra-fast, there are few successful escape outcomes.

Smoke Detection

- At a slow fire growth rate, smoke detectors are typically able to provide sufficient warning for egress past a fire within 1 m of the escape route.

- At faster fire growth rates, radiation will obstruct egress if the fire is within 1 m of the escape route, but not at any greater separation.

- As the fire growth rate speed increases, the spacing of the smoke detectors has less of an effect on the success rate. Where the fire has a fast growth rate, there is virtually 100% success where travel distances exceed 50 m, provided the fire is no closer than 3 m from the escape route.

- Where the fire growth rate is ultra-fast, the success rate is low, and typically controlled by radiation as well as tenability.

Sprinkler Protection

- Notification by sprinkler activation continues to be typically inadequate, except in large firecells, where the travel distance exceeds 60 m.

- In smaller firecells, particularly where the fire growth rate is slower, manual detection is most effective, however as the fire growth rate increases, smoke detection improves relative to manual detection, particularly where the travel distance exceeds 30-40 m.

- The firecell typically needs to be large to maintain tenability during egress, even when the fire is controlled by the sprinklers. Egress is most likely to be successful where the travel distance exceeds 50 m where dependent on manual detection, or 30 m where smoke detection is provided.

Mobile Crowd Occupancy - Retail

The differences between the analyses for office and retail *occupancies* are the *pre-movement* times and the egress travel speeds.

Firstly, consider the time available for escape, after detection and *pre-movement* as shown in Figure 4.23. This is similar to Figure 4.16, as might be expected due to the relatively small difference between the *pre-movement* times for office and retail *occupancies*, and the different angle of the line due to the slower travel speed. The resulting reduction of the number of successful escape outcomes can be more clearly seen in Figure 4.24. Where the escape route is less than 30 m, manual and smoke detection is occasionally successful, while heat detection is not. As the travel distances increase, smoke detection, and then heat detection occurs sufficiently early to allow some successful results. Once the separation distance of the fire from the escape route is 3 m or more, radiation has little influence on the success rate except when the travel distance exceeds 70 m, and manual detection provides the alert.

When the different scenarios of manual, heat, and smoke detection are reviewed (refer Appendices, Section 11 for details), similar trends to those indicated for the office *occupancy* may be seen, but generally with less success. As might be expected, there is a more pronounced trend for radiation from the fire to tend to prevent egress, due to the longer time it takes for the occupants to reach the door (slower travel speed, and longer *pre-movement* times).

For manual detection, where the travel detection exceeds 30 m, the critical separation distance is 2 m, increasing to 3 m where the travel distance exceeds 50 m, and more after 70 m.

Heat detection tends only to provide adequate notification when the travel distance exceeds 60 m. With closer spaced detectors, this could be reduced to 40 m. As above, the critical separation distance is influenced by the travel distance, and is typically 2 m, but where the travel distance exceeds 70 m, the critical separation distance is 3 m.

Smoke detectors tend to operate at an earlier time than heat detectors, and in this case generally provide adequate warning when the travel distance is no less than 40 m. This warning, however, is not adequate to permit egress within 1 m of the fire. At longer travel distances (70 m or more), if the fire is within 2 m of the escape route, radiation may still prevent egress.

The installation of sprinklers, as expected, increases the number of successful outcomes (refer to Figure 4.25). There is little difference between these successful egress rate for retail from that seen in an office environment other than a reduction in the success rate for smaller firecells (where the travel distance is less than 40 m).

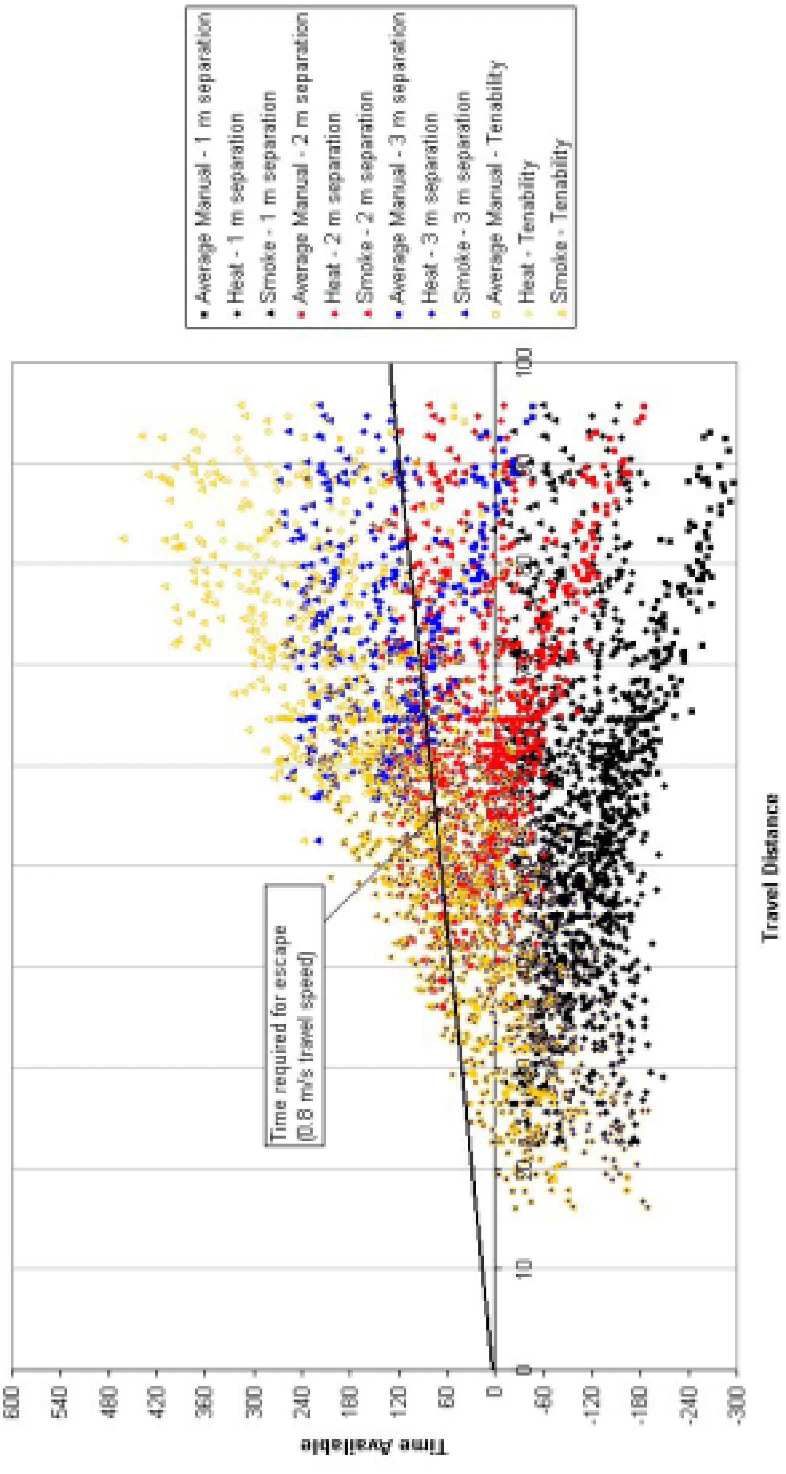

Figure 4.23 : Escape Time from Mobile Crowd Occupancy – Medium Fire Growth Rate

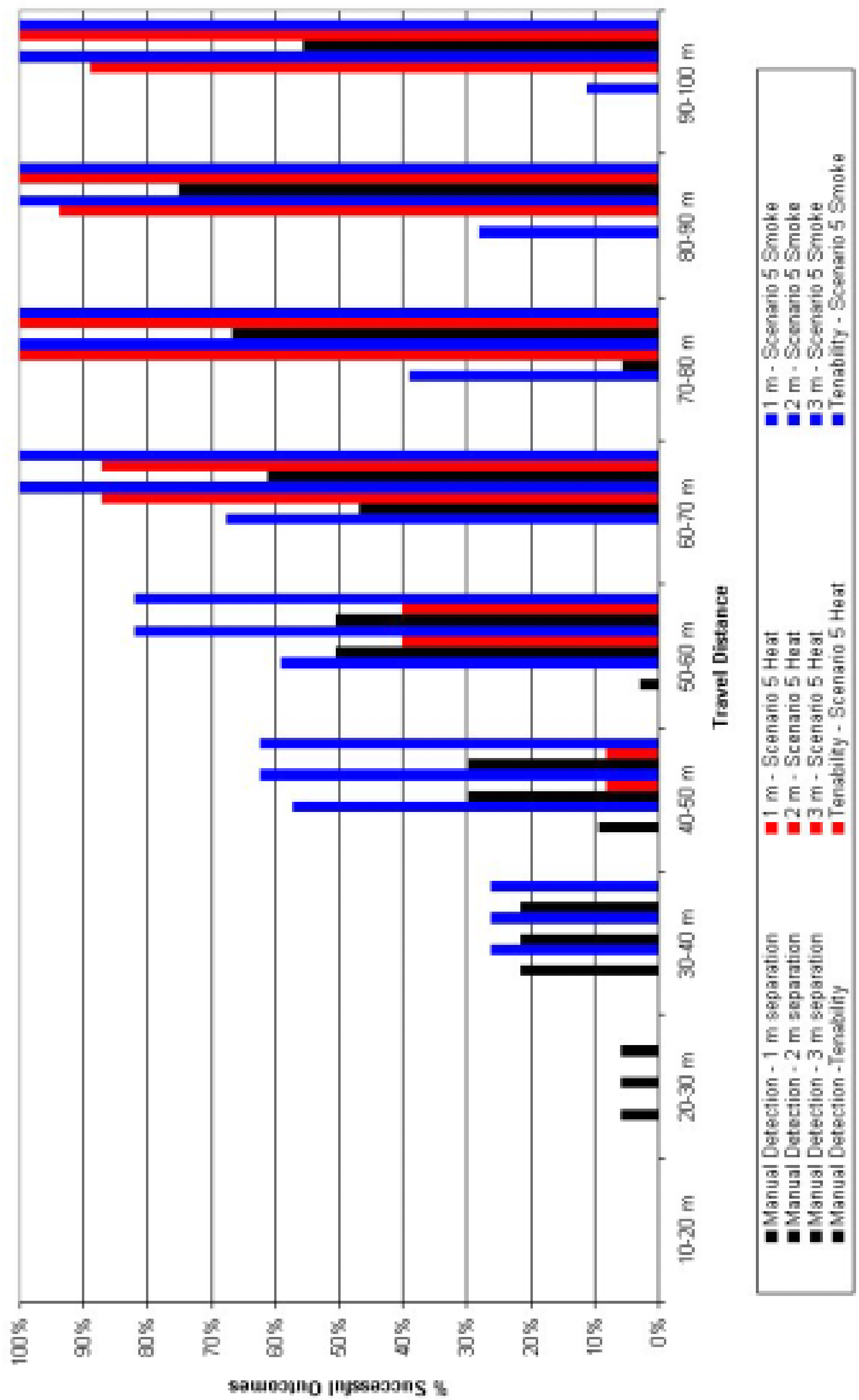

Figure 4.24 : Mobile Crowd Environment Escape Scenario Outcome Comparison – Medium Fire Growth Rate

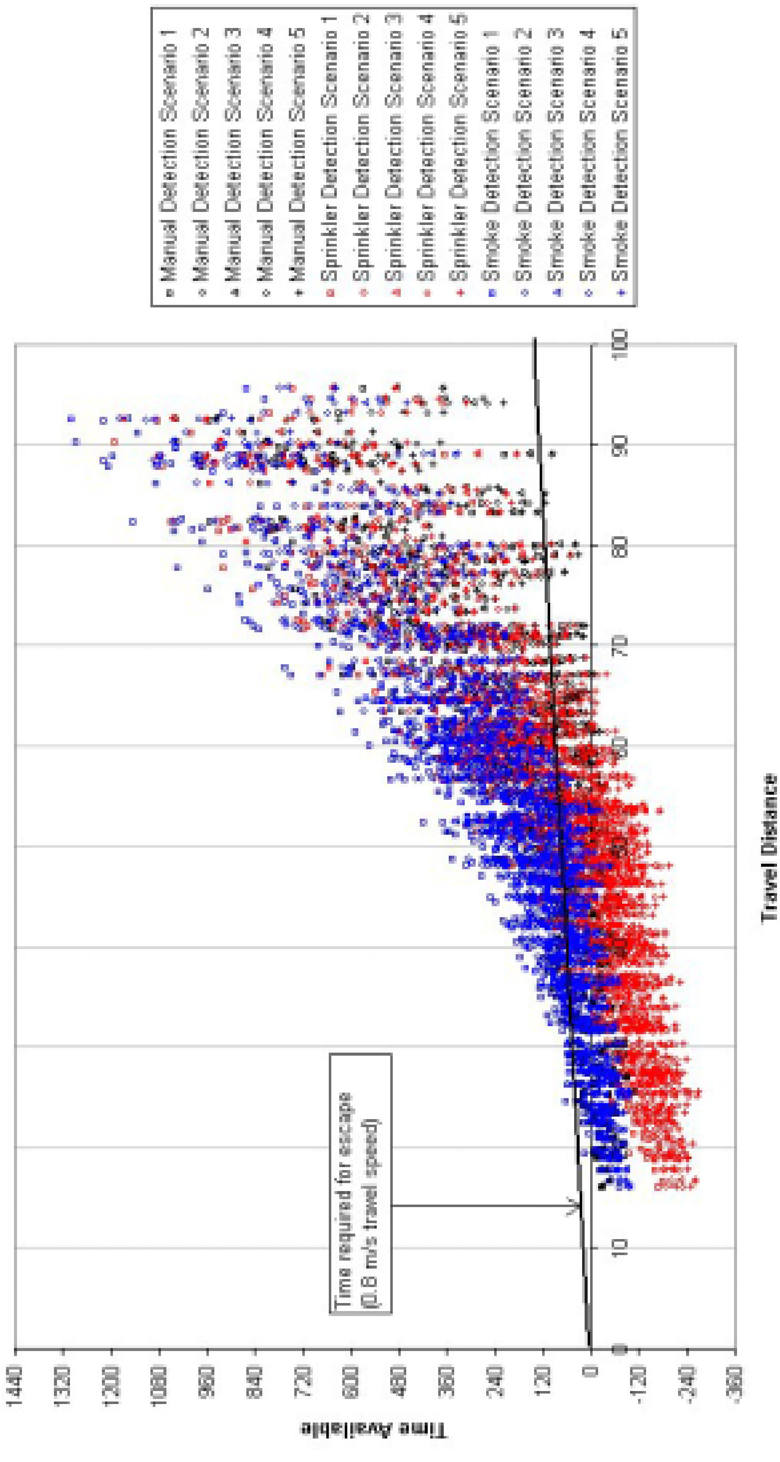

Figure 4.25 : Available Escape Time from Mobile Crowd Environment with Sprinkler Protection – Medium Fire Growth Rate

When the effects of different fire growth rates are reviewed (in the Appendices, Section 11), the following trends may be noticed.

General Detection Method Comparison

- As with the office type *occupancy*, a small number of successful egress outcomes are predicted from the smallest firecells when the fire has a slow growth rate and the fire is manually detected.

- Once the travel distance exceeds 40 m, and the fire growth rate is slow, a 2 m separation is required. At shorter travel distances radiation does not hinder egress.

- At faster fire growth rates, manual detection is typically inadequate. Smoke detection often provides adequate warning in the larger firecells, where the travel distance exceeds 60 m. Heat detection is sometimes able to provide adequate warning, but typically is not early enough.

- A 3 m or greater separation is typically required when the fire growth rate is fast.

- Where the fire has an ultra-fast growth rate, there are no outcomes with successful egress (not illustrated).

Manual Detection Scenarios

- Manual detection is reasonably adequate in larger firecells when the fire has a slow growth rate.

- When the travel distance exceeds 30 m, radiation from the fire can affect egress when within 2 m of the escape route. The critical distance increases to 3 m when the travel distance exceeds 80 m.

- There are few successful outcomes when the fire growth rate is fast or ultra-fast.

Heat Detection

- Where the fire growth rate is slow and the travel distance is less than 40 m, there are few successful outcomes. If the heat detector spacing is the maximum compliant spacing (ie scenario 5), then a 60 m travel distance is required.

Radiation from the fire can prevent egress when the fire is within 2 m of the escape route, and as the heat detector spacing increases, radiation from fires up to 3 m from the escape route may affect egress when travel distances exceed 70 m.

- Where the fire growth rate is fast, radiation from the fire will affect egress if it is within 3 m of the escape route, particularly where the travel distance exceeds 50 m. However, even in the large firecells, tenability tends to be critical and there are few successful outcomes.

- When the fire growth rate is ultra-fast, there are no successful outcomes (not illustrated)

Smoke Detection

- Where the fire growth rate is slow and the travel distance is less than 40 m, radiation does not affect egress, even at a 1 m separation of the fire from the escape route. At greater travel distances, the critical separation becomes 2 m.

- When the fire growth rate is fast, and the fire is 3 m from the escape route, radiation starts controlling egress when the travel distance exceeds 50 m.

- In smaller firecells (travel distance less than 60 m), tenability is the primary cause of failure in most outcomes.

Sprinkler Protection

- Where sprinklers are provided and the fire growth rate is slow, manual alert provides a reasonable success rate. The success rate generally becomes acceptable only in larger firecells where the travel distance exceeds 60 m.

- When the fire growth rate is fast the firecell size still needs to be such that the travel distance exceeds 60 m.

- Smoke detection is more effective than manual detection where the travel distances are shorter and the fire growth rate is faster for providing adequate warning.

Seated Crowd Occupancy - Bar

Similar trends noted in the retail *occupancy* continue in the bar *occupancy*. While the travel speed remains at 0.8 m/s, the *pre-movement* time is further increased. The time available is illustrated in Figure 4.26. The increase in *pre-movement* times is such that there is a general reduction in the occurrence of successful outcomes.

As for the other *occupancies*, the outcomes for small firecells are typically unsuccessful. The firecell size needs to be such that the travel distance is 40 m or greater before some successful outcomes are seen. These outcomes are usually dependent on smoke detector activation, and also indicate that radiation from a fire within 2-3 m of the escape route may hinder egress.

Manual detection is typically inadequate, even in the larger firecells. Some successful outcomes are predicted, but the success rate is not sufficient for this to be considered generally acceptable.

When the travel distance is less than 40 m, and heat detection is provided, a 1 m separation is typically adequate, however, when the travel distance exceeds 50 m, radiation from a fire with a 2 m separation will tend to hinder egress, making the critical separation distance 3 m. Even at this separation, egress in response to more widely spaced heat detectors from a firecell with a 90 m travel distance could be hindered by radiation.

Similar to the trend noted in the effect of radiation from the fire, the warning from smoke detectors is typically sufficiently early that radiation is unlikely to impede egress if the fire is within 2 m of the escape route and the travel distance is no greater than 50 m. At longer travel distances, the required separation increases to 3 m. However, the earlier warning of the smoke detectors does improve the available tenability time, and giving a high success rate where the travel distance exceeds 70 m. In contrast, where heat detectors are provided, a similar success rate is not achieved below an 80 m travel distance.

Finally, assessing the effects of sprinkler control (refer to Figure 4.27), the delay caused by *pre-movement* time significantly reduces the available escape time before tenability is lost. While a travel distance of 50 m still provides adequate tenability time to egress in most cases, the number of successful outcomes from smaller firecells is significantly reduced from those observed earlier in office and retail situations. As noted previously in the retail situation, smoke detection is increasingly beneficial, and tending to occur before manual detection in the larger firecells.

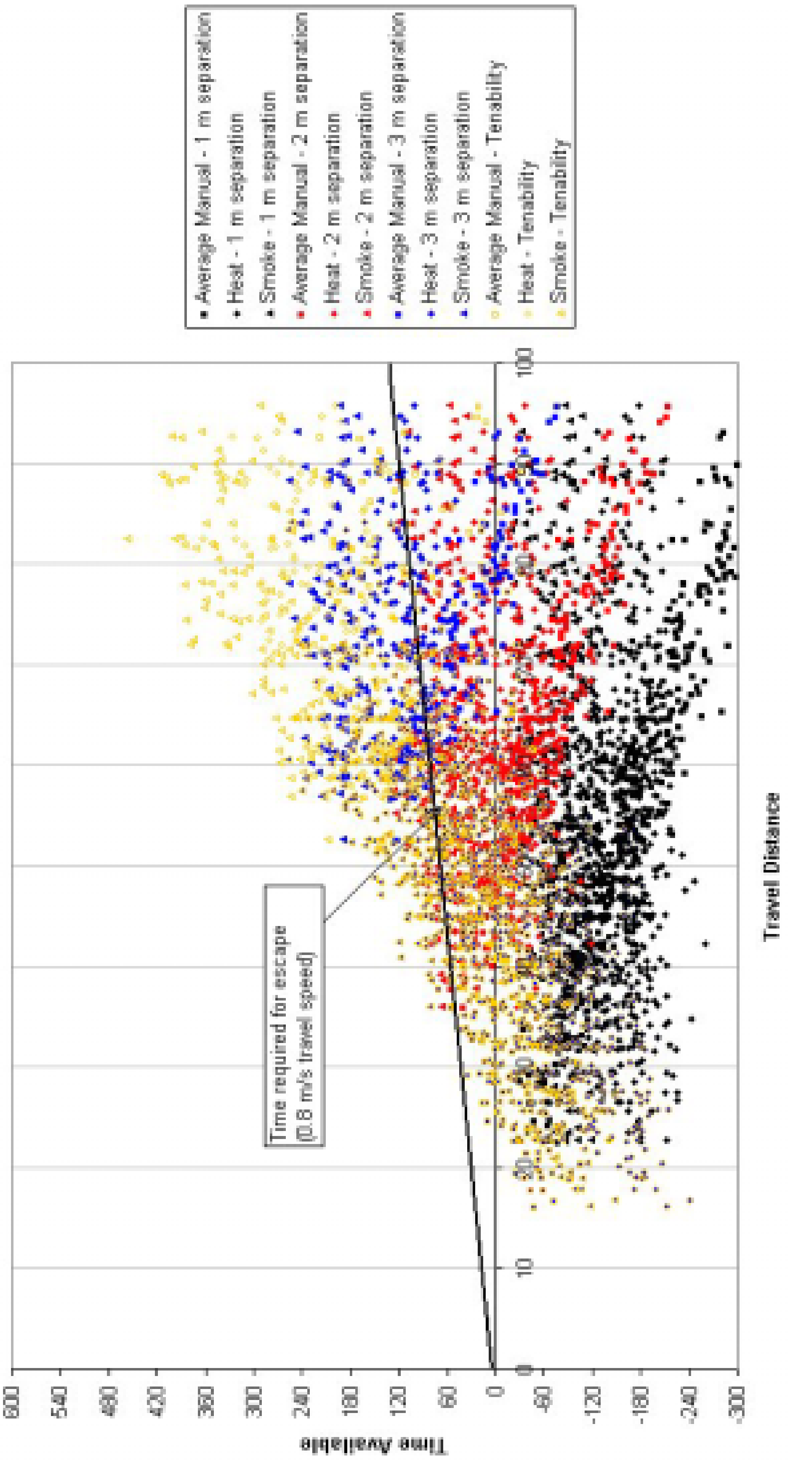

Figure 4.26 : Escape Time from Seated Crowd Environment – Medium Fire Growth Rate

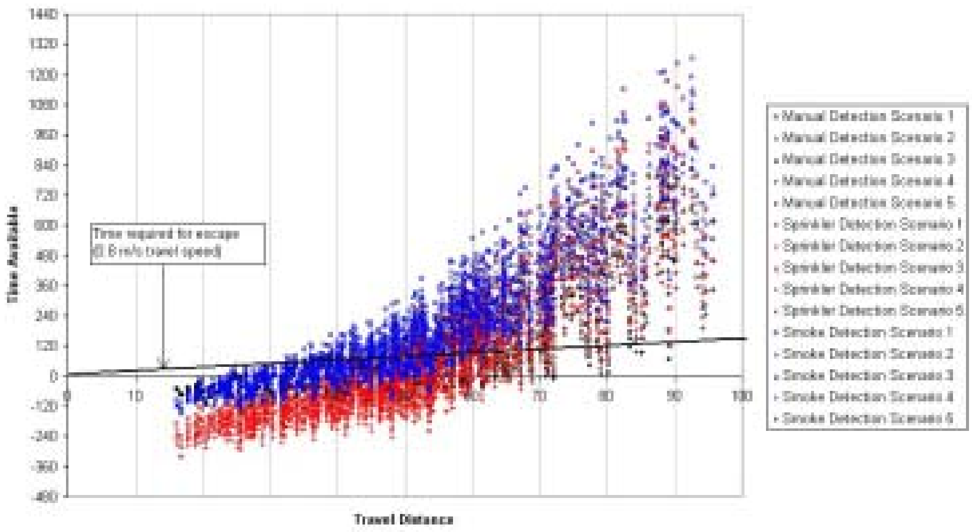

Figure 4.27 : Available Escape Time from Sprinkler Protected Seated Crowd Environment – Medium Fire Growth Rate

When other fire growth rates are considered the following trends can be seen:

General comparison of Detection Methods

- Where the fire growth rate is slow, manual detection occurs before automatic detection, particularly in smaller firecells (travel distance less than 50 m)
- Where the growth rate is slow, there is little obstruction due to radiation when the fire is close to the escape route. Only when the travel distance exceeds 40 m is a 2 m separation required.
- Where the fire growth rate is fast, there are few successful outcomes. Those that are successful result from smoke detector activation, and the fire being further than 3 m from the escape route.
- There are no successful outcomes when the fire growth rate is ultra-fast.

Manual Detection Scenarios

- Manual detection is typically adequate when the fire growth rate is slow and the travel distance exceeds 40 m, however at these distances a 2 m or greater separation between the fire and the escape route is required.
- When the fire growth rate is fast or ultra fast, there are no successful outcomes.

Heat Detection Scenarios

- Where the fire growth rate is slow, a 2 m separation is typically required to prevent radiation hindering egress.
- The firecell size needs to be relatively large (travel distance exceeding 60 m) for the outcomes to be typically successful.
- Where the fire growth rate is fast, radiation from the fire will hinder egress if within 3 m of the escape route. Otherwise, tenability is generally critical, with successful outcomes generally occurring only when the detectors are installed at closer spacings.

Smoke Detection Scenarios

- As noted in the heat detection scenarios (also for a slow fire growth rate), a 2 m separation is typically required between the fire and the escape route to prevent excessive radiation.
- Where travel distances exceed 50 m, the outcome is typically successful.
- For fast fire growth rates, as for the heat detection scenario, radiation will generally hinder egress if the fire is within 3 m of the escape route. Where the travel distance exceeds 60 m, there is a reasonable chance of a successful outcome provided radiation does not hinder escape.

Sprinkler Protection

- If the fire growth rate is slow, manual detection will typically occur before smoke detection, but if it is fast, smoke detection will precede manual detection.

- During a slow fire, a reasonable success rate is reached when the travel distance exceeds 60 m, but in a fast, and even an ultra-fast fire, a similar success rate is not reached where the travel distance is less than 70 m.

4.1.5 Summary of t^2 Fire Analyses

The trends and comments made in the preceding sections are summarised in Table 4.4, and the following comments are provided to repeat the more important results:

- As this study is primarily addressing firecells with only single means of escape, the situation where two escape routes from the firecell are provided, with a shorter *dead end* escape route to reach the alternative route, has not been addressed. However, these results could also be applied to that situation. The effect of radiation from the fire could also be used to assess the separation required between different escape routes, or to aid in the positioning of a critical item, ensuring it is sufficiently distant from an escape route.

- The manual detection time is calculated based on a smoke layer thickness. The model includes no improvements for when occupants may be in close proximity and hence receive other cues. This, while conservative for large firecells (where the most distance occupants have an equal opportunity to detect the fire), this may be unreasonably slow for small firecells where the occupants will all be in closer proximity to the fire.

- The *pre-movement* times calculated are typically not related to the conditions at detection, with the exception of the various manual detection scenarios. Therefore, in smaller firecells, where smoke from the fire is likely to alarm occupants earlier, and reduce the time taken for *pre-movement* activities, these times are very conservative.

- The available evacuation time is typically dependent on the plan area of the firecell, with relatively little dependence on the ceiling height.

- Manual detection is frequently predicted to occur before smoke detection, particularly in smaller firecells, and in almost all cases it will precede heat detection.

- The risk of a fire obstructing an egress route is typically very low. The risks calculated earlier assume that the route may be blocked at a single point, and will be relatively higher if the arrangement of the escape routes has several such control points.

- The separation required between the fire and the escape route is mainly dependent on the fire growth rate. The travel time to reach the fire has relatively little influence on it's size, particularly as the greatest proportion of the time required to evacuated the firecell is in the *pre-movement* times.

- Sprinkler operation typically controls the fire to a size that permits egress within approximately 1.5 m of the fire. Therefore, radiation is unlikely to affect egress. The primary reason for egress failure is therefore the tenability time. For the same reasons as noted above, the unsuccessful outcomes in small firecells are not considered to be realistic. The threat of the fire, including other cues from the proximity of the fire are likely to result in reduced detection and *pre-movement* times than those assumed in this analysis.

Occupancy and Detection		Slow Fire Growth Rate	Medium Fire Growth Rate	Fast Fire Growth Rate	Ultra-Fast Fire Growth Rate
Office	Manual	1 m separation adequate up to 60 m travel distance, then need 2 m separation. Good success rate where travel distance > 30 m. Some success in small firecells.	2 m separation required, increasing to 3 m where travel distance exceeds 70 m. Most successful where travel distance > 60 m.	Few successful outcomes, generally controlled by tenability rather than radiation.	No successful outcomes.
	Heat	1 m separation adequate up to 50 m travel distance, then need 2 m separation. Good success rate when travel distance > 60 m. Closer detector spacings could reduce this by 10-20 m.	2 m separation required for all travel distances. Most successful where travel distance > 60 m. Closer spacings would permit reducing this by 10-20 m.	2 m separation up to 40 m travel distance, but further than this, require 3 m separation. When travel distance exceeds 60 m, radiation at 3 m may still affect. Most successful at 60 m travel distance, but could reduce this by 10 m if spacings reduced.	Few successful outcomes, none when separation < 3 m.
	Smoke	1 m separation adequate for all firecell sizes. Best success rate when travel distance > 40 m.	2 m separation required. Adequately successful (~90%) when travel distance > 40 m.	2 m separation required for travel distances < 50 m. Above this, require 3 m separation. Most successful when travel distance > 50 m.	Few successful outcomes, none when separation < 3 m.

	Sprinklers	A few successful outcomes in small firecells. Manual detection best when travel distance < 50 m, then smoke detection improves. When manual detection, best success at 60 m + travel distances, or 40 m + when smoke detection.	Manual and smoke detection similar, but smoke better once travel distance > 30 m. Acceptable success rate for smoke detectors where travel distance > 40 m, 60 m for both manual and sprinkler alert.	Smaller firecells typically unsuccessful. Smoke detection typically gives earlier warning than manual detection. Smoke detector warning mostly successful then travel distance > 50 m, manual detection is successful when travel distance > 60 m.	Smaller firecells lose tenability too fast. When travel distance > 60 m, success rates for manual and smoke detection are similar.
Retail	Manual	1 m separation adequate up to 40 m travel distance, then 2 m is adequate up to 80 m. 3 m separation required for 90 m travel distance. Reasonable success rates when travel distance 50 m and greater.	Few successful outcomes – only 50% success rate at best (or average) detection where travel distance > 50 m. 2 m separation required up to 40 m travel distance, 3 m up to 70 m, > 3 m required for larger firecells.	No successful outcomes	No successful outcomes.
	Heat	2 m separation adequate for most travel distances, but some interference when travel distances > 80 m. Reasonable success when travel distance > 60 m.	Best success rates when travel distance > 60 m. 2 m separation does not obstruct egress when travel distance less than 50 m, but 3 m separation needed in bigger firecells.	Radiation typically hinders if fire within 3 m of the escape route. Tenability times generally inadequate when travel distance less than 90 m, although close spacing of heat detectors would give acceptable warning for 60 m and greater distances.	No successful outcomes.

	Smoke	1 m separation adequate up to 30 m travel distance, but above that, 2 m separation required. Acceptable success rates reached when travel distance > 50 m.	Best success rates then travel distance greater than 50 m. 2 m separation will not hinder egress for most travel distances, but 3 m separation best for travel distances > 60 m, particularly for maximum compliant detector spacings.	3 m separation required up to 50 m travel distance, then greater separation required for longer travel distances. Adequate warning provided for firecells with travel distance > 60 m.	No successful outcomes.
	Sprinklers	Manual detection earlier than smoke detection when travel distance less than 40 m. Acceptable success rates reached when travel distance > 50 m (smoke) and 60 m (manual) detection.	Smoke detector typically provides earlier warning, and best success when travel distance > 50 m. If no smoke detection, need to > 60 m.	Smoke detection precedes manual detection. Acceptable egress success when travel distance > 60 m (smoke) and 70 m (manual)	Smoke detection precedes manual detection. Acceptable Success rates when travel distance > 70 m.
Bar	Manual	A 2 m separation is required where travel distance exceeds 40 m. Up to that size, 1 m generally adequate.	Few successful scenarios, generally where the fire is not within 3 m of the escape route.	No successful outcomes.	No successful outcomes.
	Heat	A 2 m separation is typically adequate. Acceptable success rate occurs when travel distance greater than 60 m.	A separation of 3 m is typically required. Acceptable levels of successful outcomes do not occur below travel distances of 60 m.	Few successful outcomes – separation required to be greater than 3 m. Some chance of success when travel distance > 50 m, but only a small chance	No successful outcomes

Smoke	A 2 m separation is typically adequate. Acceptable success rate where travel distance greater than 50 m.	A 2 m separation is adequate for smaller firecells, but 3 m is required where the travel distance is greater than 50 m. Successful outcomes, assuming separation provided, occur when travel distance it 60 m or greater.	3 m separation will not hinder when travel distance less than 40 m. When travel distance is 50 –60 m, there is 50% chance of success, increasing as the travel distance increases.	No successful outcomes.
Sprinklers	Manual detection earlier than smoke detection when travel distance less than 30 m. Acceptable success rates reached when travel distance > 60 m (smoke) and 70 m (manual) detection.	Smoke detection typically occurs before manual detection. Travel distances of 60 m (smoke) and 70 m (manual) are required for acceptable egress success rates.	Smoke detection typically occurs earlier than manual detection. Acceptable success routes reached when travel distance > 60 m (smoke) and 70 m (manual)	Smoke detection occurs earlier than manual detection. Acceptable success routes reached when travel distance > 70 m for both.

Table 4.4 : Summary of Analysis Results

4.2 Item Fires

As noted in Section 3, a number of specific item fires will be considered in this assessment. These have been taken from Särdqvist (1993) as well as from the NIST web-site, and are summarised in Table 4.5. Those marked with an asterix (*) have been analysed more fully in the following section. The heat release rates for these fires are given in the following figures (as referenced in the Table). These item fires have been selected as the heat release rate graphs indicate that these items have the highest heat release rate, or longest peak within the group of items selected.

Category and Figure		Reference Number	Description
Office Figure 4.28		Y0/20	Room furnished with an office module. The partitions were forming a U, with a desk on one side and a file cabinet on the other. As fire failed to develop, these particular results will not be used.
	*	Y0/21	Similar to Y0/20, with rearrangement of papers on the desk
	*	Y0/22	Computer work station with a computer desk and a bookcase at right angles to each other. Computer desk: The desk had a set of 4 shelves above and a small cabinet under the top. Free burning
		Y0/23	Same as Y0/22, but in a room
Wardrobes Figure 4.29		Y3.1/10	Simulated clothing: Four different fabrics placed into the wardrobes on 16 clothes hangers. Steel wardrobe, painted
		Y3.1/11	“Clothes” as above (typical) Plywood wardrobe
		Y3.1/12	Particleboard wardrobe with drawers and shelves
	*	Y3.1/13	Plywood wardrobe with rolling door – unfinished
		Y3.1/14	Plywood wardrobe with rolling door – FR Latex paint on inside
		Y3.1/15	Plywood wardrobe with rolling door - 2 coats FR latex paint inside and out

Bookcases Figure 4.30		Y3.3/11	Bookcases, containing X-ray records Paper envelopes containing paper and plastic X-ray plates.
		Y3.3/12	Open shelving unit with paper. Distance between units 0.7 m. Four open shelving units, each with 5 steel shelves. Bottom shelves (1 & 2) contain 37 kg horizontally stacked paper. Shelves 3 & 4 : 14 kg paper in open top vertical file holders Shelf 5 : 19 kg paper in closed cardboard boxes.
	*	Y3.3/13	Open shelving units with paper as described above. Two boxes with paper products were placed in the aisle between the units. Total mass: 3 kg. Distance between the units : 0.61 m
Chairs, Stackable Figure 4.31		Y5.0/10	Stackable plastic chairs. Neither padding nor cushions. Seat and back: Polypropene (one piece) Legs : Metal. Single Chair
		Y5.0/11	5 chairs in one row, middle chair ignited
		Y5.0/12	8 chairs in four rows, chair in second row ignited
		Y5.0/13	6 chairs in one stack, top chair ignited
	*	Y5.0/14	12 chairs in 2 stacks, top chair ignited
		Y5.0/15	Metal framed chairs containing approx 0.5 kg PU foam and 2kg celluslosic materials Single Chair
		Y5.0/16	4 chairs in 1 stack
		Y5.0/17	8 chairs in one stack
		Y5.0/18	8 chairs in one stack, burned in the corner of a standard room
Easy Chairs Figure 4.32	*	Y5.3/10	Wooden frame, polyurethane foam, polyolefin fabric Size and mass: 0.84 x 0.84 x 0.81 m^3, 28.34kg
		Y5.3/11	Frame: One-piece moulded polystyrene with plywood inserts. Polyurethane foam, polyolefin fabric cover. Size and mass: 0.84 x 0.84 x 0.81 m^3, 11.52kg
		Y5.3/12	Wooden frame, polyurethane foam, cotton fabric, 0.91 x 0.91 x 0.81 m^3, 15.68kg
		Y5.3/13	Wood reinforced polyurethane foam, metal springs with 25-50 mm polyester batting, polyurethane foam imitation leather cover. 0.84 x 0.84 x 0.76 m^3, 15.98kg.
		Y5.3/14	Wooden frame, polyurethane foam, polyester filled cushions, cotton fabric cover, 0.84 x 0.84 x 0.76 m^3, 23.02 kg

Sofas Figure 4.33	*	Y5.4/21	3-seat sofa, wooden frame, polyurethane foam filling, polyolefin fabric cover, 0.84 x 2.0 x 0.81 m³, 51.5 kg.
		Y5.4/22	Loveseat, metal frame, polyurethane foam covered with a layer of cotton, plastic coated fabric cover, 0.84 x 1.32 x 0.72 m³, 27.3 kg
		Y5.4/23	Loveseat. Oak wood frame, polyurethane foam with cotton layer, plastic coated fabric cover, end panels of 9.5 mm plywood with polyurethane padding and plastic coated fabric cover, 0.81 x 1.37 x 0.76 m³ cover, 54.6 kg.
NIST Tests	*	Figure 4.34, Figure 4.35	Small Dresser
	*	Figure 4.36, Figure 4.37	3-panel workstation
	*	Figure 4.38, Figure 4.39	2-panel workstation
	*	Figure 4.40, Figure 4.41	Sofa
	*	Figure 4.42, Figure 4.43	Loveseat

Table 4.5 : Design Fire Information

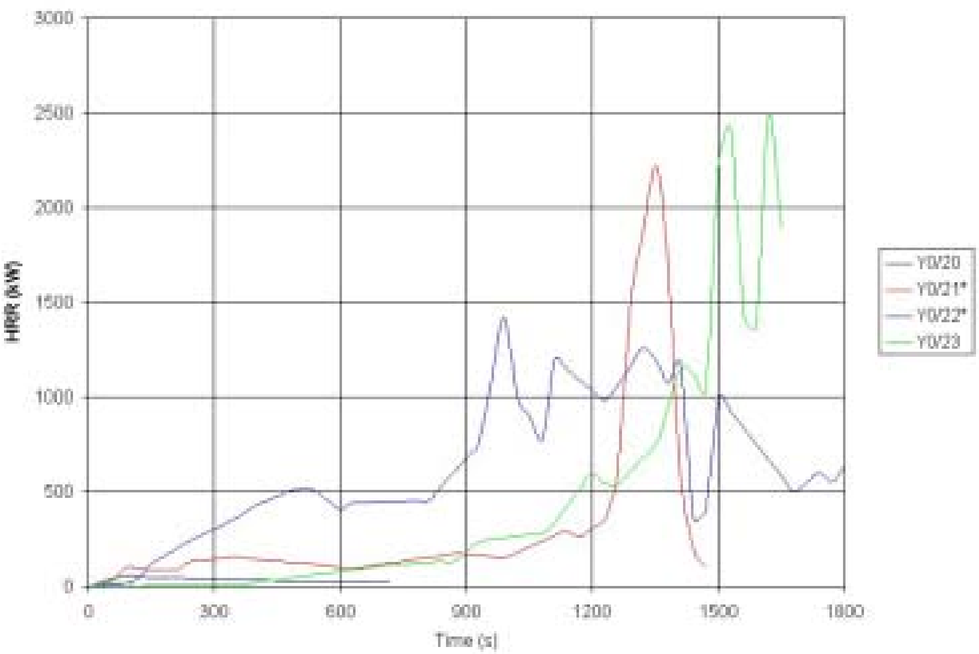

Figure 4.28 : Office Workstation Heat Release Rates

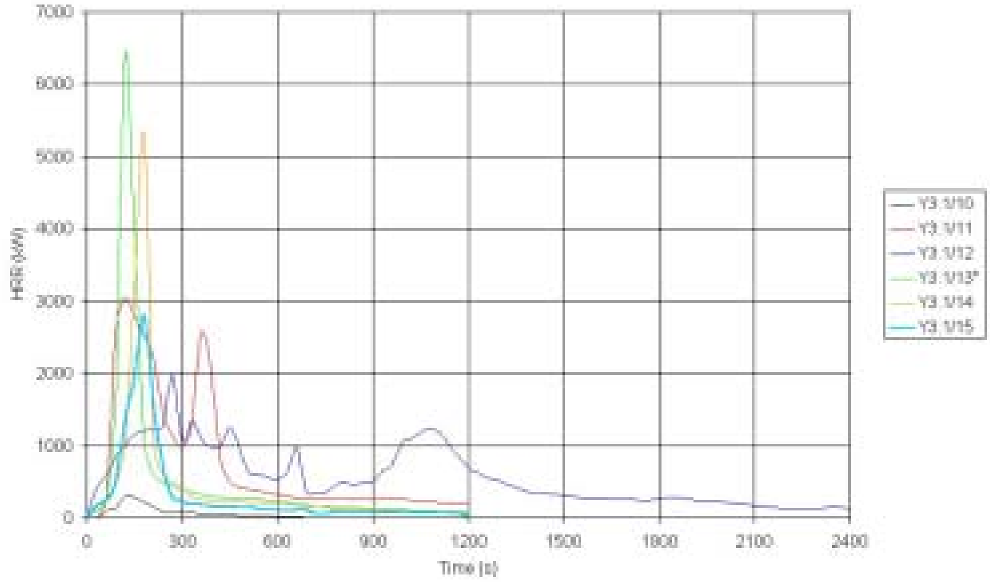

Figure 4.29 : Wardrobe Heat Release Rates

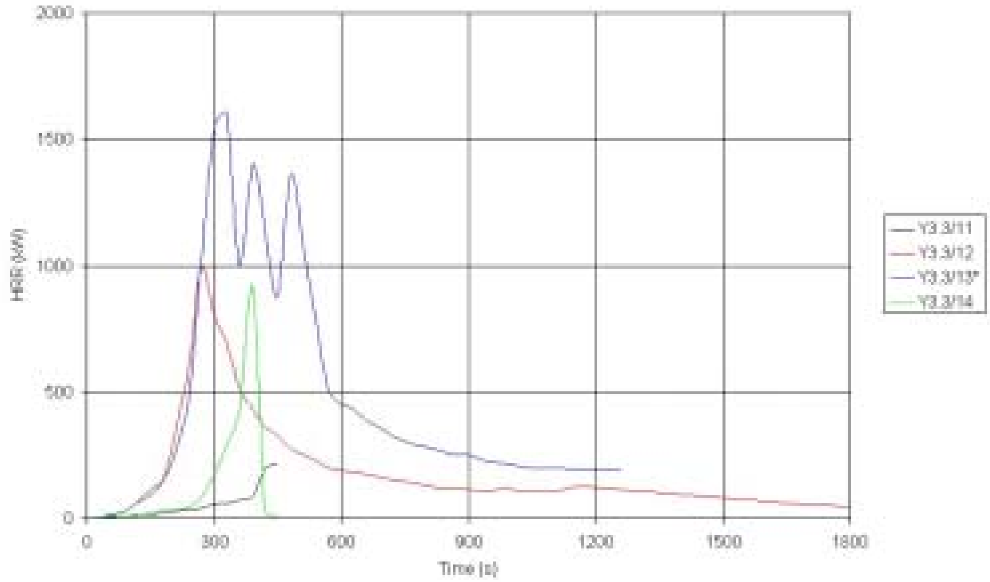

Figure 4.30 : Book Case & Storage Heat Release Rates

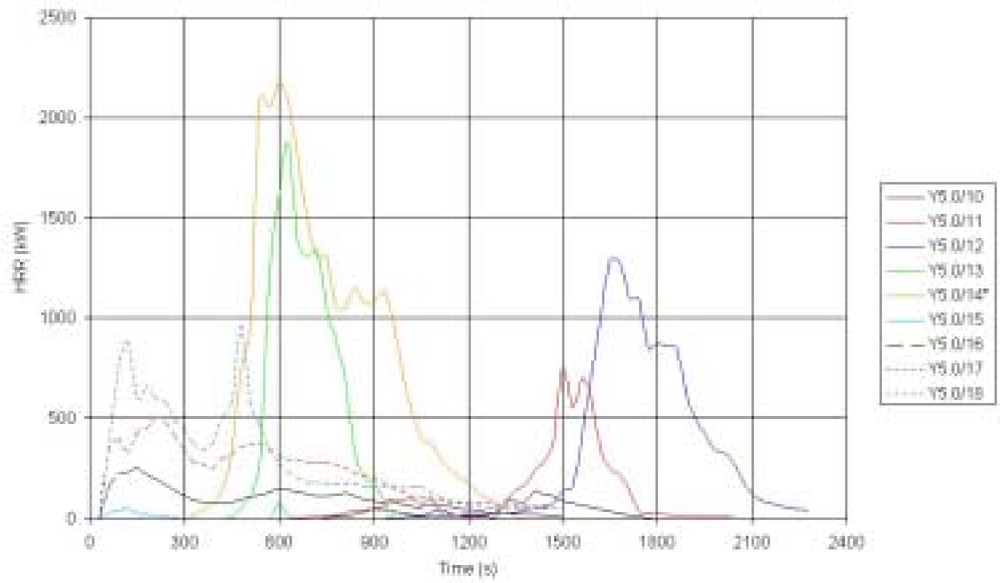

Figure 4.31 : Stackable Chairs Heat Release Rates

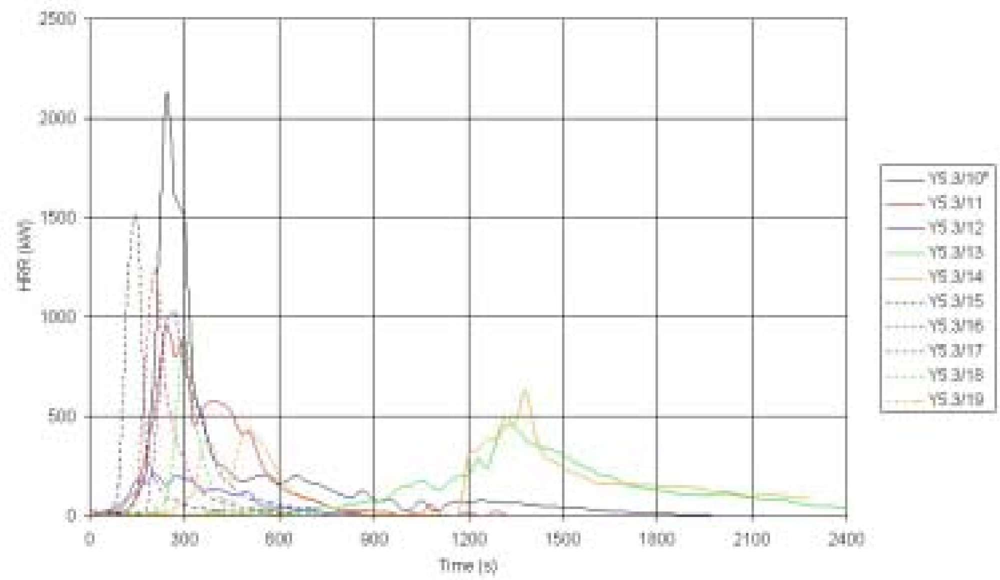

Figure 4.32 : Easy Chair Heat Release Rates

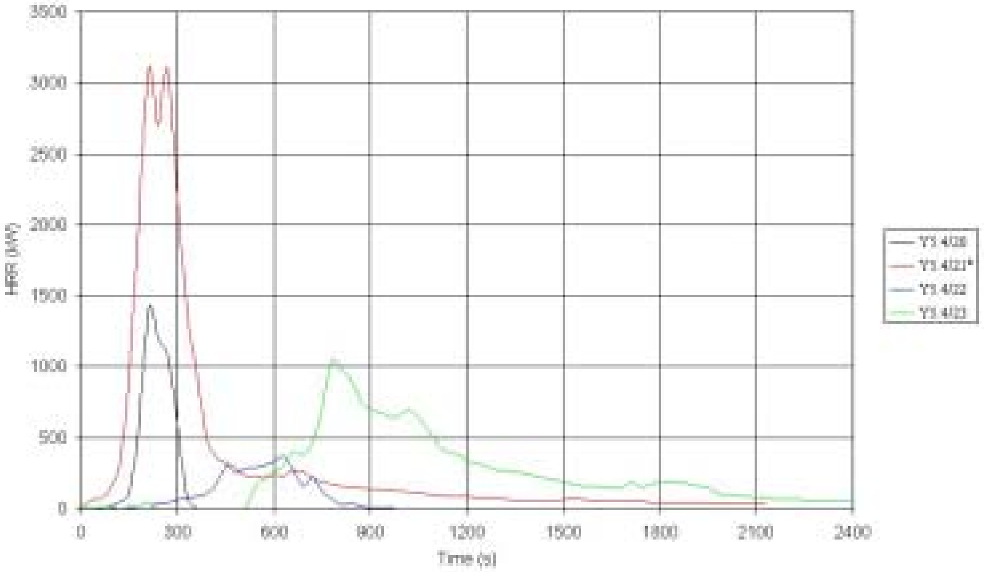

Figure 4.33 : Sofa Heat Release Rates

Figure 4.34 : Small Dresser

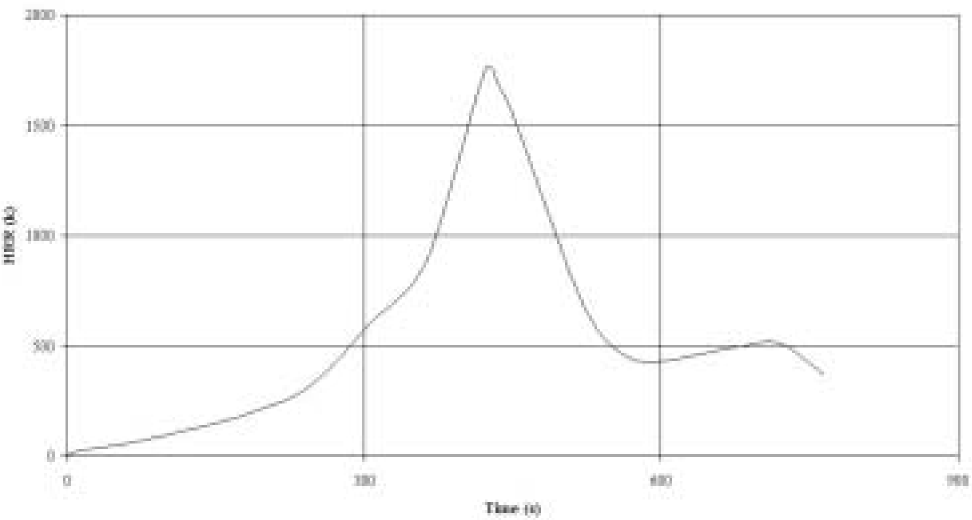

Figure 4.35 : Small Dresser Heat Release Rate

Figure 4.36 : 3-Panel Workstation

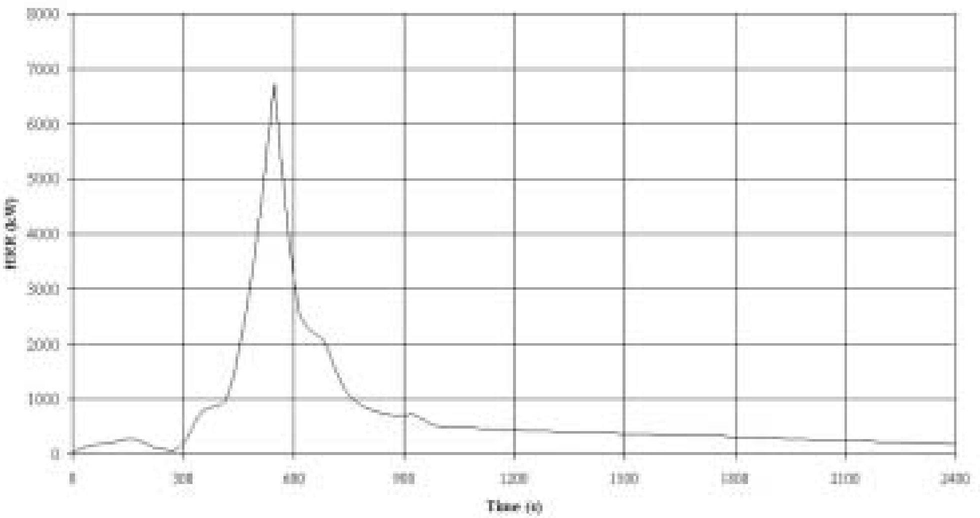

Figure 4.37 : Heat Release Rate for 3-Panel Workstation

Figure 4.38 : 2-Panel Workstation

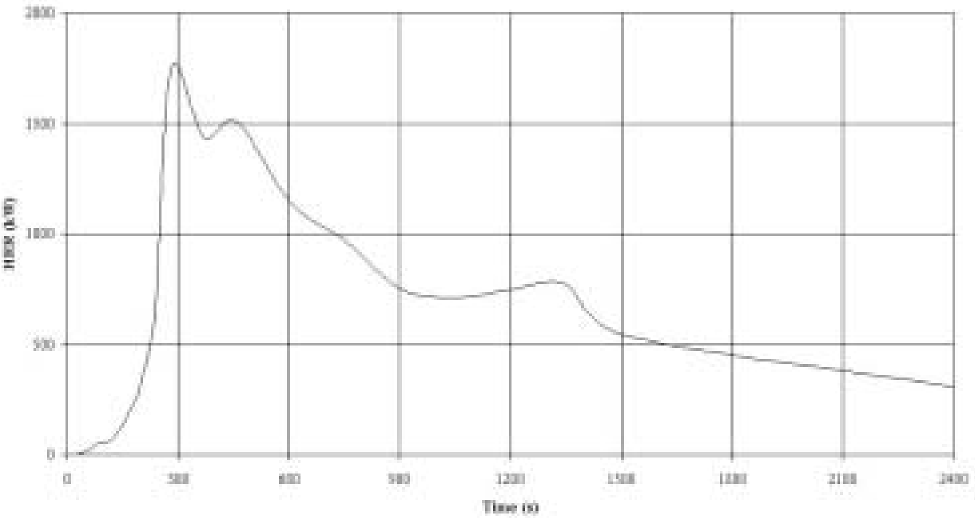

Figure 4.39 : Heat Release Rate for 2-Panel Workstation

Figure 4.40 : Sofa

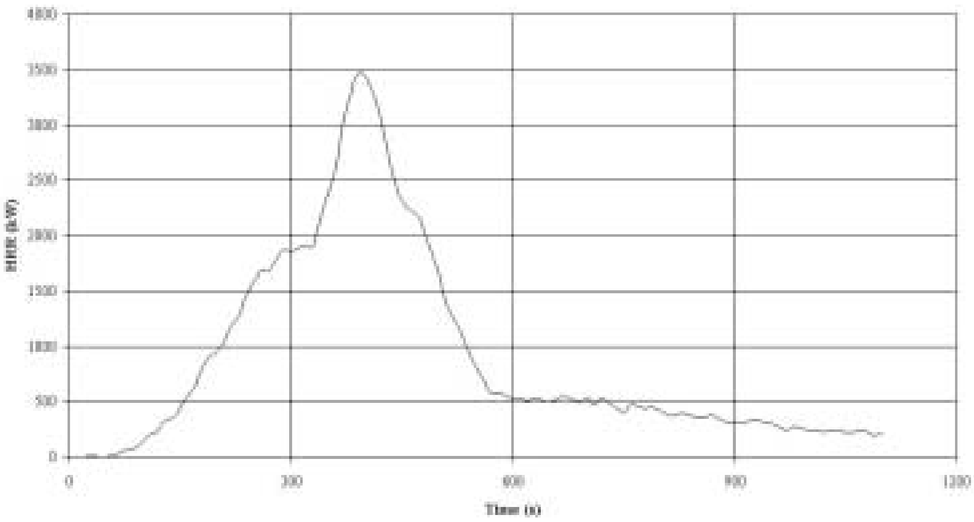

Figure 4.41 : Heat Release Rate for Sofa

Figure 4.42 : Loveseat

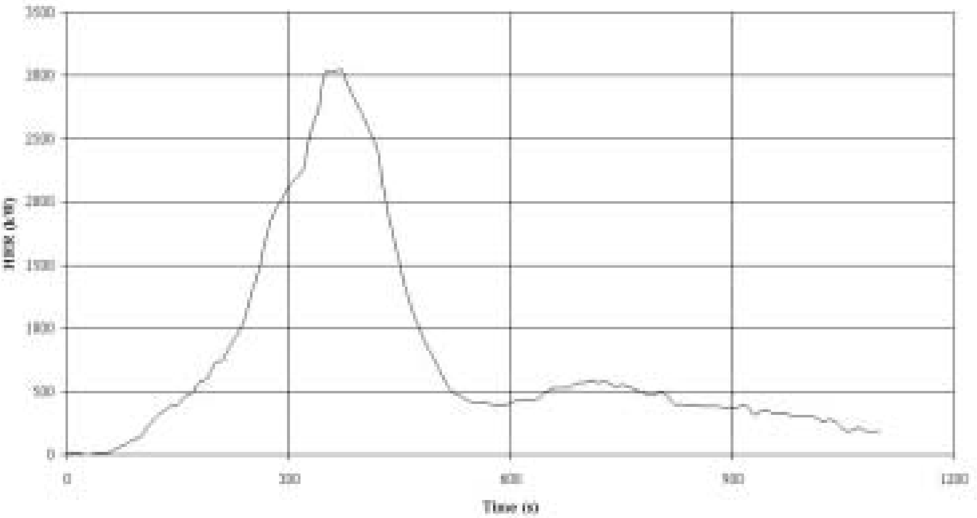

Figure 4.43 : Heat Release Rate for Loveseat

4.2.1 Analysis of Item Fire Results

The risks associated with an item fire in a firecell may also be assessed using the same techniques as for the t² fires in the previous section. It is expected that the uneven growth rates, particularly the slow start followed by the rapid development that can be seen in most of the heat release rate graphs will have an effect on the conditions in the firecell and near the escape route.

Office Furniture Fires: Y0/21, Y0/22, 2 Panel Workstation & 3 Panel Workstation

The furniture involved in these fires is typically found in an office environment, although could also be present in some crowd environments (eg the managers office). The safety of office occupants in the same firecell will first be assessed, followed by crowd occupants. Given the different (uneven) fire growth rates, it is necessary to re-calculate the time at which the fire reaches a size that cannot be passed at various speeds and separation distances. These are shown in Table 4.6.

Fire Description	1.2 m/s travel speed (work)			0.8 m/s travel speed (crowd)		
	1 m 536 kW	2 m 1607 kW	3 m 3069 kW	1 m 295 kW	2 m 1031 kW	3 m 2173 kW
Y0-21 Office Module	1250 sec	1300 sec	Not reached	1140 sec	1275 sec	1350 sec
Y0-22 Office Module	840 sec	Not reached	Not reached	270 sec	960 sec	Not reached
3 Panel Workstation	323 sec	438 sec	484 sec	307 sec	420 sec	487 sec
2 Panel Workstation	240 sec	280 sec	Not reached	195 sec	255 sec	Not reached

Table 4.6 : Office Furniture Fires - Limiting Fire Times for Egress Separation

The first feature of the analysis to be noted is the two distinct sets of results in Figure 4.44. This is related to the shape of the heat release rate curve for test Y0/21 (shown in Figure 4.28), which stays relatively low (200-300kW) for a substantial period of time, before climbing rapidly to approximately 2200 kW, then dropping off just as rapidly. The lower points in Figure 4.44 are mostly scenarios dependent on heat detector activation. The fire does not get sufficiently large at an early stage to activate these detectors, but the smoke produced over the longer period of time allows manual detection to occur relatively early. Although the fire is too small to activate heat detectors at this point, smoke detectors are still sufficiently sensitive to also provide adequate warning of such a fire.

The other office furniture heat release rate, Y0/22, has a higher plateau (at closer to 500 kW), and a lower, more sustained peak (between 1000 kW and 1500 kW). This plateau is high enough for earlier activation of heat detectors, and the peak is low enough to permit egress reasonably close to the fire.

Reference to Figure 4.48 and Figure 4.49 confirm that in neither of these cases is obstruction by the fire likely to control egress, as manual and smoke detection both occur sufficiently early to allow egress past the fire while still small. As noted before, heat detectors typically operate too late to allow egress while the room is still tenable, let alone while the fire is small enough not to obstruct the escape route.

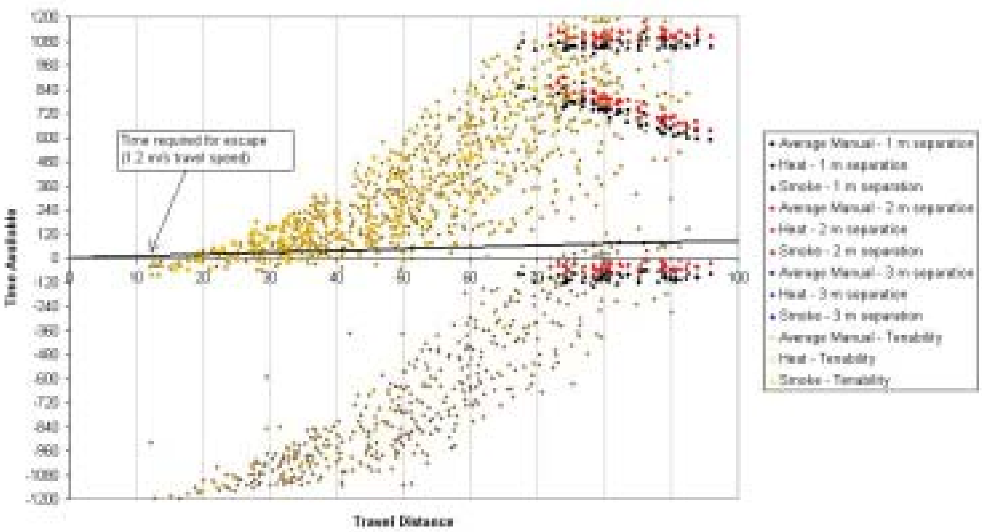

Figure 4.44 : Available Escape Time from Y0/21 Office Furniture Fire in Work Environment

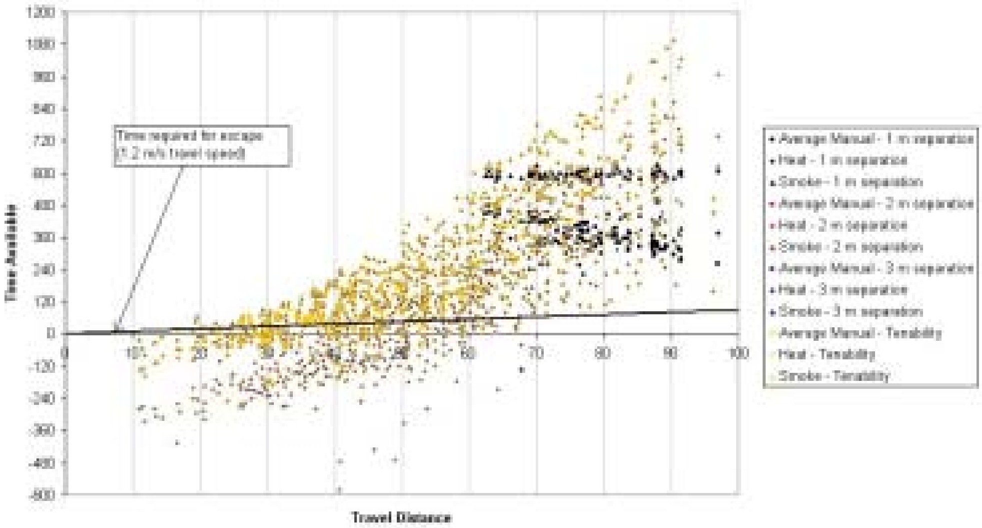

Figure 4.45 : Available Escape Time from Y0/22 Office Furniture Fire in Work Environment

The heat release rates from the NIST tests for the 2 and 3 panel workstations (refer Figure 4.36 and Figure 4.37) show the same tendency for a short plateau, before a quick growth to reach the peak heat release rates. However, the peak in the 3 panel workstation test is much greater than those observed in the other tests, and the plateau is shorter in both tests, particularly in the 2 panel workstation test.

The shorter plateaus mean that the early warning from manual and smoke detection is not as significant in Figure 4.46 and Figure 4.47 in comparison to Figure 4.44 and Figure 4.45. Also noticeable in Figure 4.46 is that the tenability times can be quite long. This is due to the relatively short, contained duration of the fire, hence the limited quantity of smoke produced may not result in loss of tenability in the space. The size of peak heat release rates in both tests, however, is such that the fire could prevent egress if within 2-3 m of the escape route.

Reference to Figure 4.50 and Figure 4.51 confirm this, and also clarify the extent of the obstruction problem. With the 2 panel workstation, the risk of obstruction increases with the travel distance. In smaller firecells, where the travel distance is less than 20 m, obstruction has no effect on the success rate, but as the travel distance increases, the critical separation distance increases past 2 m to 3 m. The initial plateau in the 3 panel workstation test means that the earlier warning before the heat release rate peaks provides time to pass the fire before it peaks and obstructs the route.

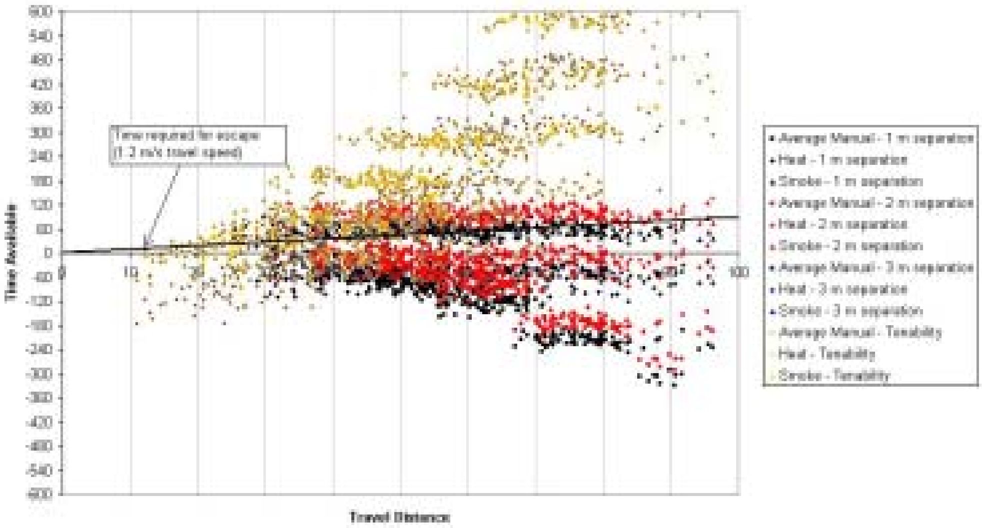

Figure 4.46 : Available Escape Time from 2 Panel Workstation Fire in Work Environment

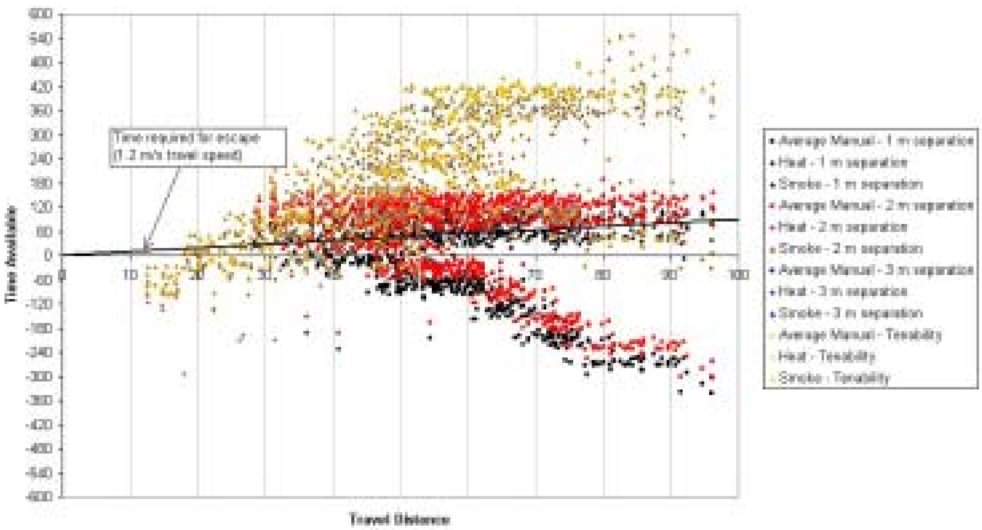

Figure 4.47 : Available Escape Time from 3 Panel Workstation Fire in Work Environment

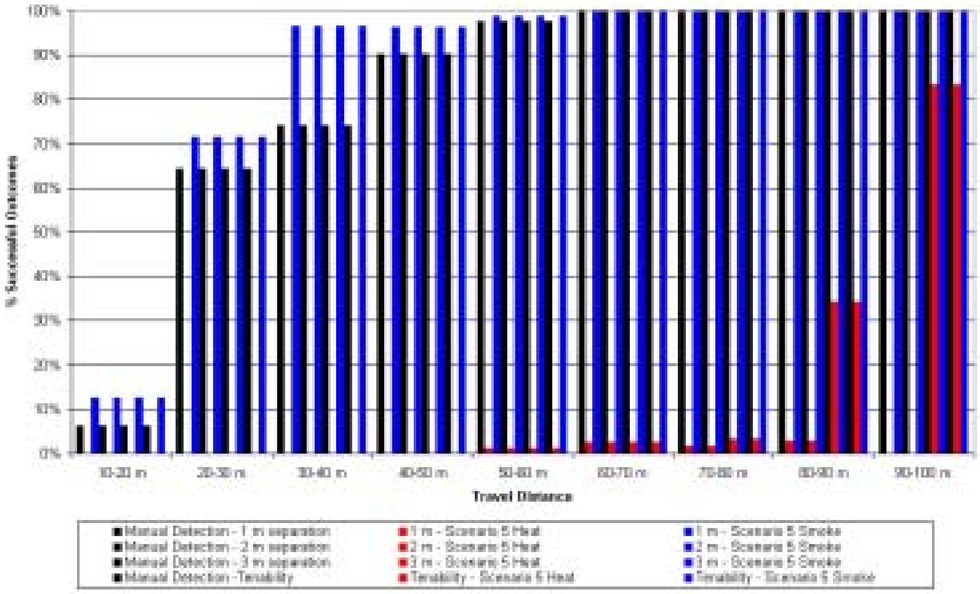

Figure 4.48 : Work Environment Egress Scenario Outcome Comparison – Y0/21 Office Furniture Fire

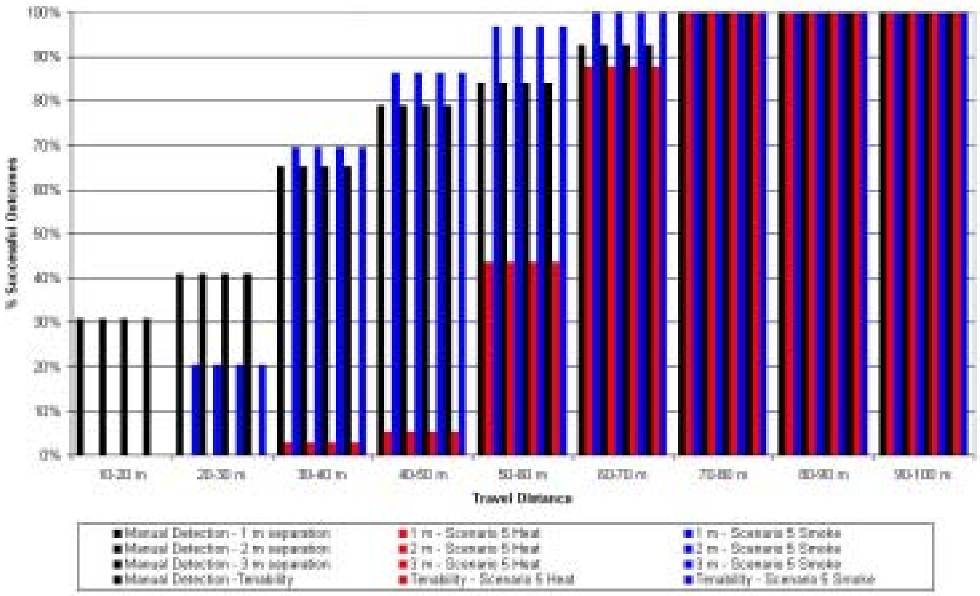

Figure 4.49 : Work Environment Egress Scenario Outcome Comparison – Y0/22 Office Furniture Fire

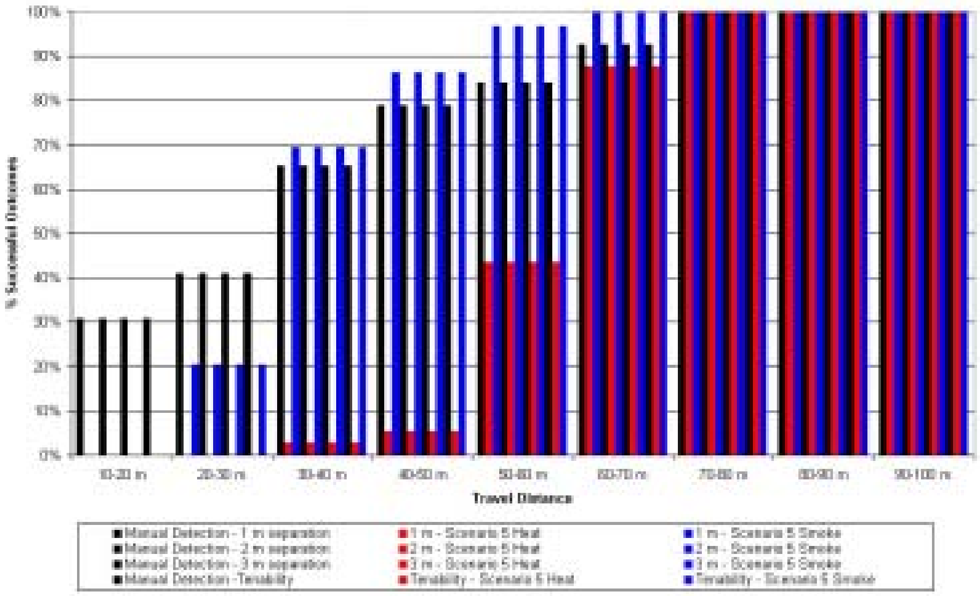

Figure 4.50 : Work Environment Egress Scenario Outcome Comparison – 2 Panel Workstation Fire

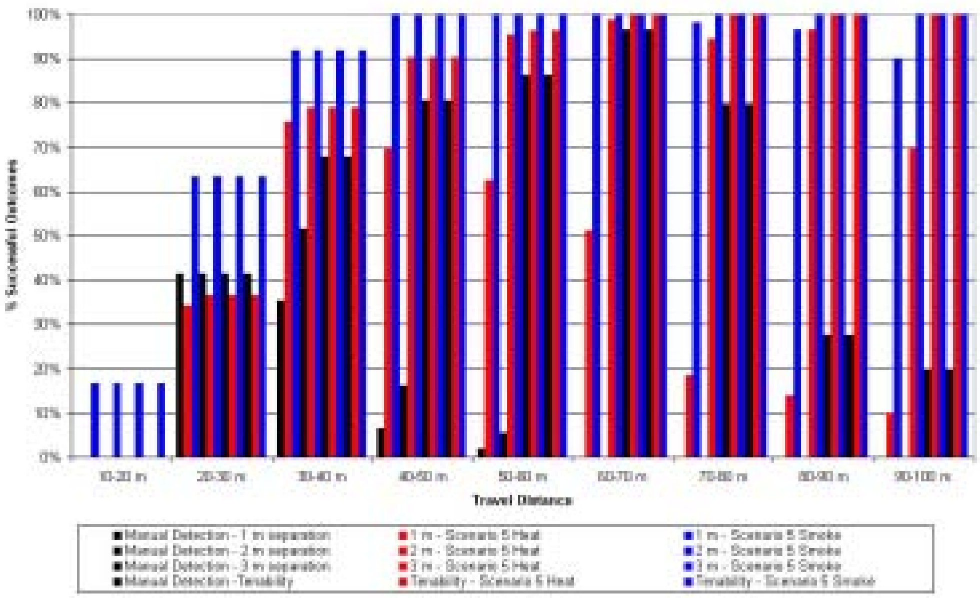

Figure 4.51 : Work Environment Egress Scenario Outcome Comparison – 3 Panel Workstation Fire

When sprinklers are installed, a similar pattern can be seen in the Y0/21 Office furniture fire in Figure 4.52. The low heat release rate plateau fails to activate the sprinklers, so successful egress is dependent on manual or smoke detection, allowing egress before tenability is lost.

In Figure 4.53, results for the sprinkler controlled Y0/22 Office furniture fire are shown. This graph is also very similar to the results for the medium fire growth rate scenario comparison in Figure 4.21. Despite the differences between Figure 4.52 and Figure 4.53, Figure 4.56 and Figure 4.57 remain remarkably similar. These confirm that response to either manual or smoke detection gives a fairly high chance of successful egress, whereas response to sprinkler activation will more than likely be too late.

The 2 and 3 panel workstation fire graphs, in Figure 4.54 and Figure 4.55, show this same trend, which is also continued in Figure 4.58 and Figure 4.59.

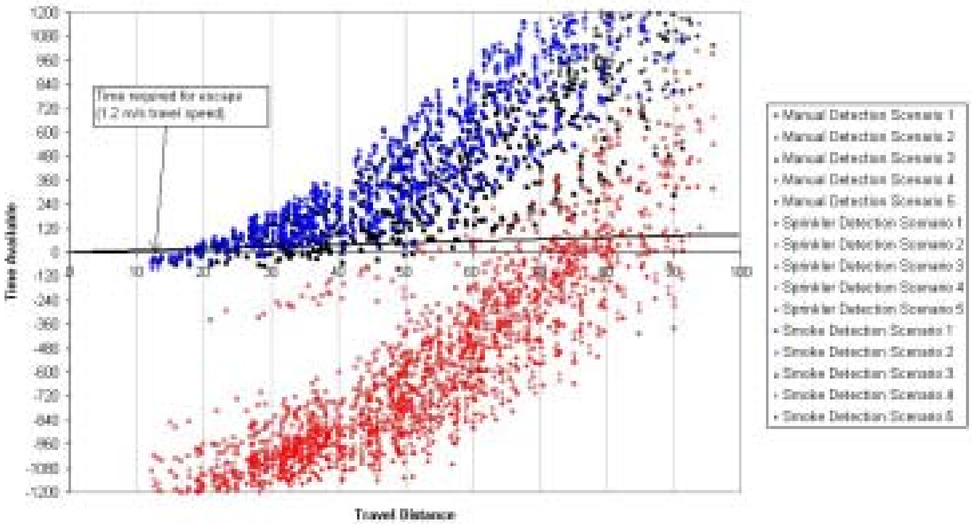

Figure 4.52 : Available Escape Time from Sprinkler Protected Work Environment – Y0/21 Office Furniture Fire

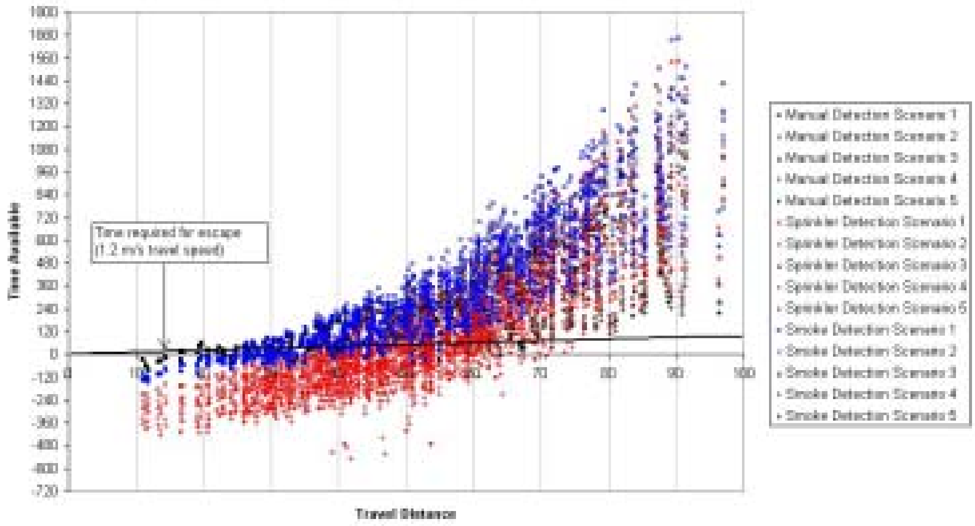

Figure 4.53 : Available Egress Time from Sprinkler Protected Work Environment – Y0/22 Office Furniture Fire

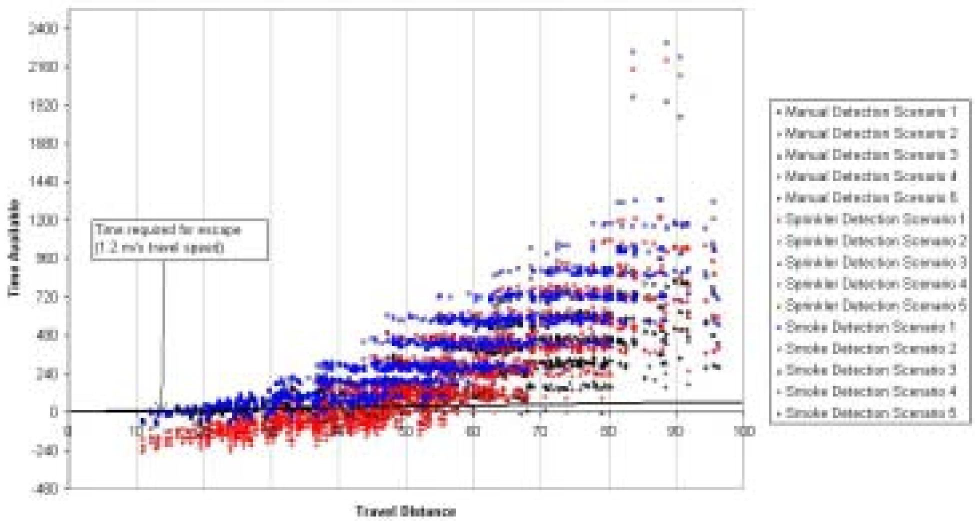

Figure 4.54 : Available Egress Time from Sprinkler Protected Work Environment – 2 Panel Workstation Fire

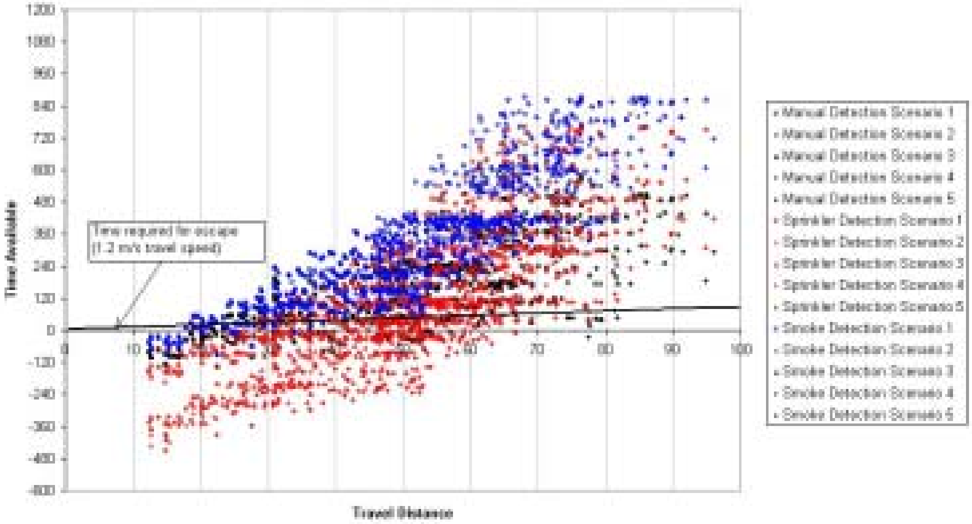

Figure 4.55 : Available Egress Time from Sprinkler Protected Work Environment – 3 Panel Workstation Fire

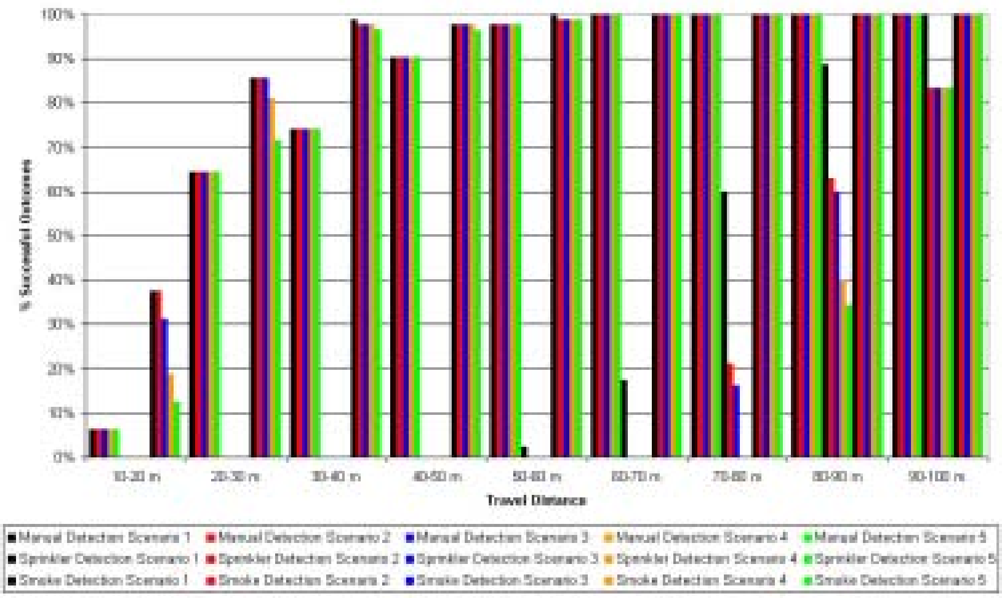

Figure 4.56 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Y0/21 Office Furniture Fire

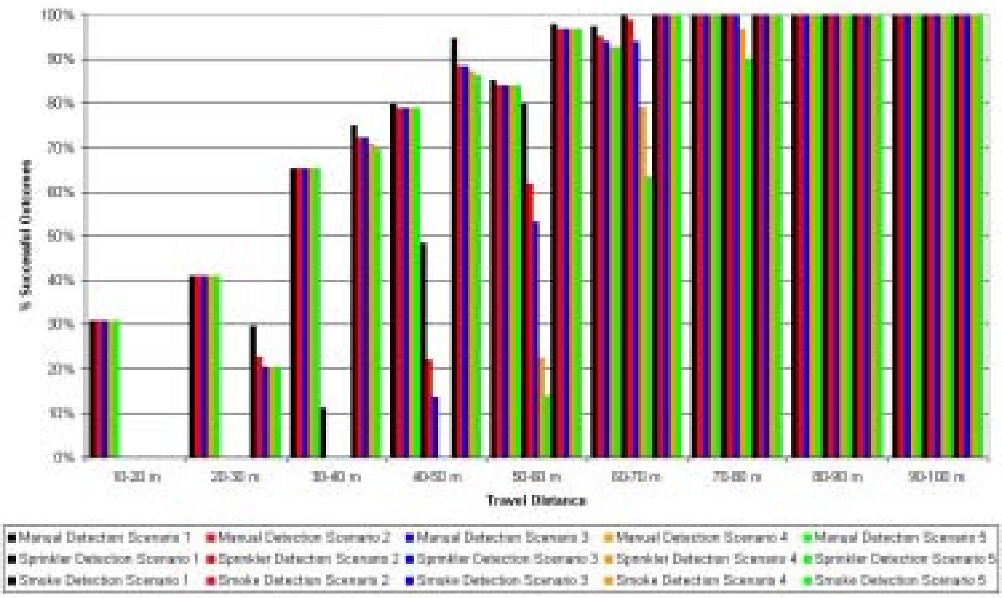

Figure 4.57 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Y0/22 Office Furniture Fire

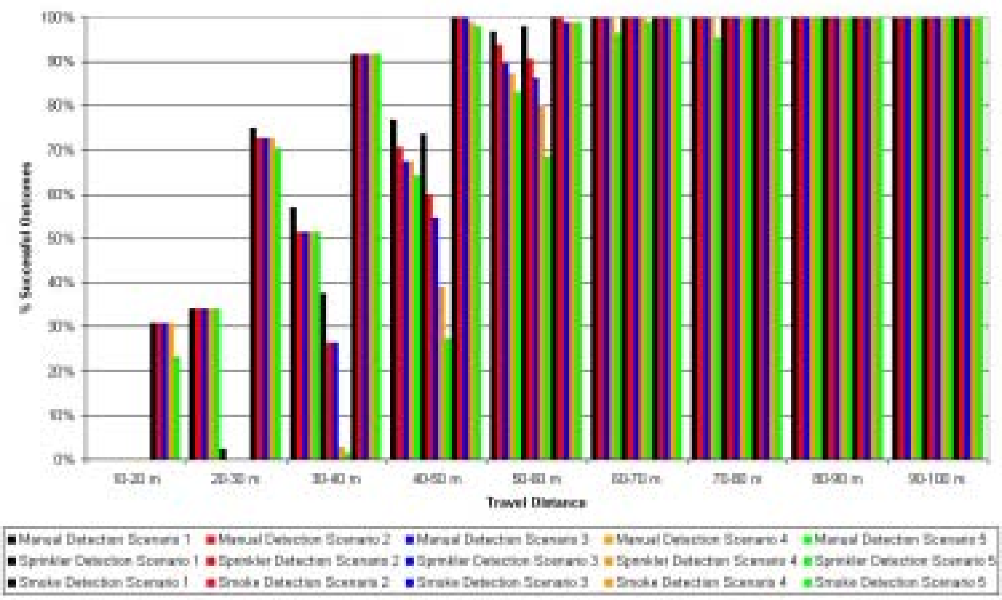

Figure 4.58 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison - 2 Panel Workstation Fire

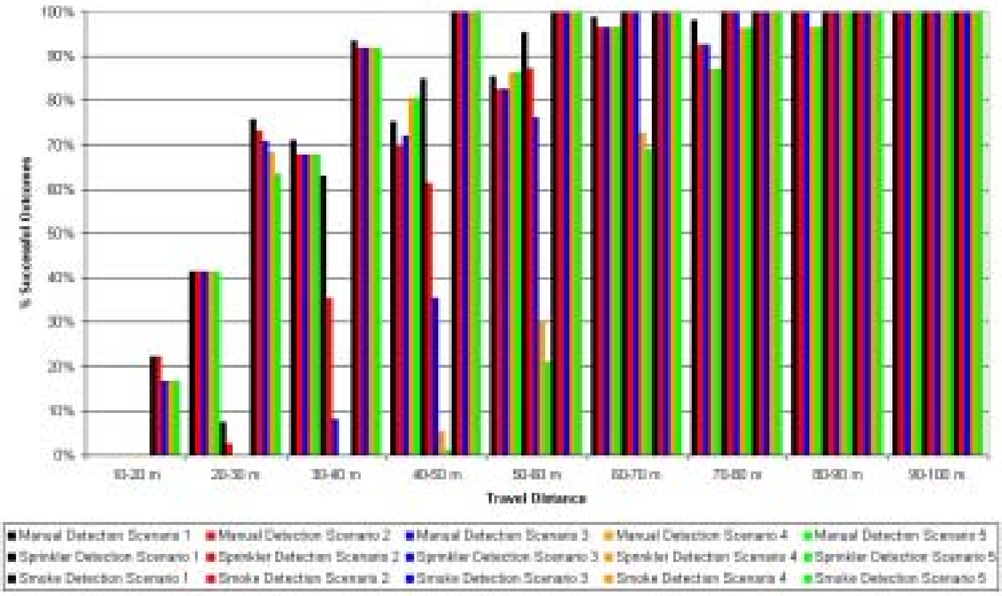

Figure 4.59 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – 3 Panel Workstation Fire

<u>Mobile Crowd Environment with Office Furniture Fire</u>

When these office furniture fires are placed into a crowd environment, such as a shop, the occupants will tend to take longer to decide whether to evacuate, and due to the larger numbers of people at a higher occupant density, they will move more slowly. The particular furniture here, involving papers, desks, and computers, surrounded by part-height partitions, is unlikely to be located in the same room or space as the crowd. Therefore, obstruction of an egress route is unlikely. However, most, if not all, shops have a counter, often with a computer or cash register for sales and stock tracking. Such an arrangement is unlikely to have the higher fuel loads and peak heat release rates exhibited in some of the examples, although the Y0/22 office furniture fire could reasonably occur in this situation.

The results of these analyses, shown in the Appendices, Section 12, confirm the trends noted previously. In a mobile crowd, or retail situation, manual and smoke detection give the most adequate warning, although when in a large firecell, heat detection may also provide adequate warning. A 2 m separation between the fire and the egress route is adequate all of these scenarios.

When a seated crowd, such as in a bar or restaurant, is exposed to such a fire, the increased *pre-movement* time means that the success rate is significantly lower. In particular, the failures are due to the increased fire size at the time of egress, and the consequently greater radiation to the escape route, obstructing egress. Such furniture would need to be located further than 3 m from the escape route to allow a reasonable expectation of success, even for the shorter travel distances.

Soft Furnishing Fires: Y5.0/14, Y5.3/10, Y5.4/21, Loveseat & Sofa.

The furniture involved in these fires may be found in a variety of environments, from office receptions, to furniture stores, and even bars and restaurants. The safety of office occupants in the same firecell will first be assessed, followed by retail and bar occupants. As before, it is necessary to calculate the time at which the fire reaches a size that cannot be passed at various speeds and separation distances. These are shown in Table 4.7.

Fire Description	1.2 m/s travel speed (work)			0.8 m/s travel speed (crowd)		
	1 m 536 kW	2 m 1607 kW	3 m 3069 kW	1 m 295 kW	2 m 1031 kW	3 m 2173 kW
Y5.0/14 Stackable Chairs	465 sec	530 sec	Not reached	440 sec	515 sec	540 sec
Y5.3/10 Easy Chair	195 sec	230 sec	Not reached	185 sec	215 sec	240 sec
Y5.4/21 3-Seat Sofa	130 sec	170 sec	270 sec	120 sec	152 sec	185 sec
Loveseat (2-Seat Sofa)	180 sec	270 sec	370 sec	120 sec	240 sec	310 sec
Sofa (3-Seat)	160 sec	250 sec	370 sec	130 sec	210 sec	340 sec

Table 4.7 : Soft Furnishing Fires - Limiting Times for Egress Separation

As can be inferred from Figure 4.60, Figure 4.61, and Figure 4.62, the growth rate of these fires is relatively quick, and there is generally insufficient warning to allow egress within 2-3 m of the fires (unless the maximum heat release rate is less than 2000 kW). In the case of the loveseat and sofa fires, where the available escape time is illustrated in Figure 4.63 and Figure 4.64 respectively, the growth rate of these fires is considerably slower. This can be confirmed by comparing the heat release rate curves given in Figure 4.32, Figure 4.33, Figure 4.41, and Figure 4.43. The slower growth rate means that the occupants have more time to escape before the fire obstructs them, and it can be seen that the graphs for these fires have a greater number of scenarios “above the line” indicating successful egress within 2-3 m of the fire. This is confirmed in Figure 4.68 and Figure 4.69.

First, reference to Figure 4.65, Figure 4.66, and Figure 4.67 indicates that successful egress from these spaces is affected if the fire is within 3 m of the escape route. In some small firecells, where the travel distance is less than 30 m, tenability tends to be the controlling condition, with a very small number of successful scenarios at all separations.

In Figure 4.68 and Figure 4.69 the slower growth rate means that there is a greater success rate where egress is within 2 m of the escape route, and at short travel distances, even less separation is required.

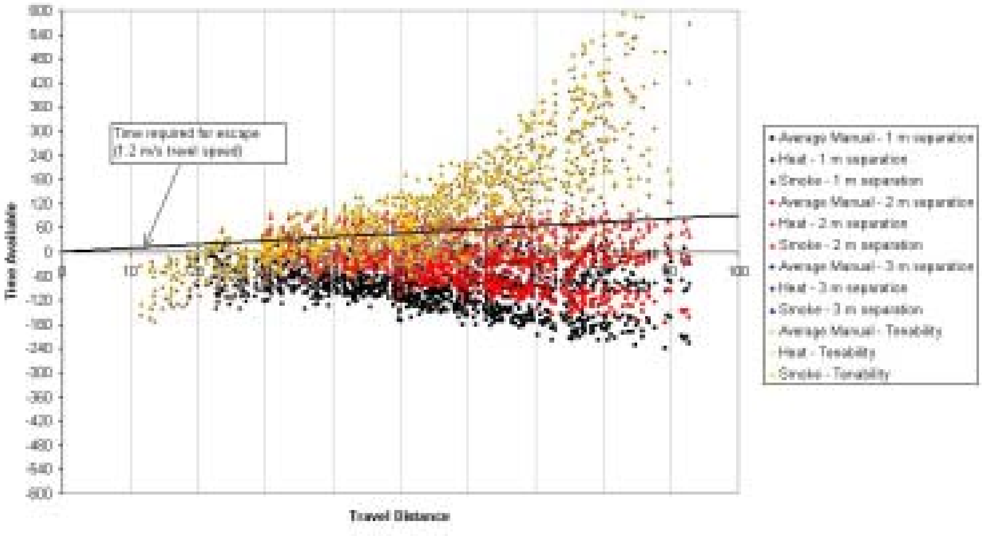

Figure 4.60 : Available Escape Time from Work Environment – Y5.0/14 Stackable Chair Fire

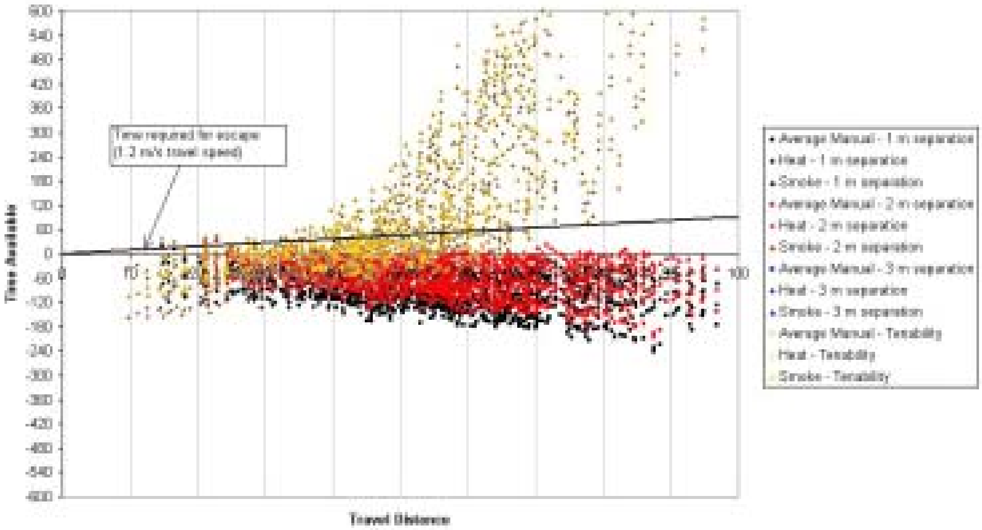

Figure 4.61 : Available Escape Time from Work Environment – Y5.3/10 Chair Fire

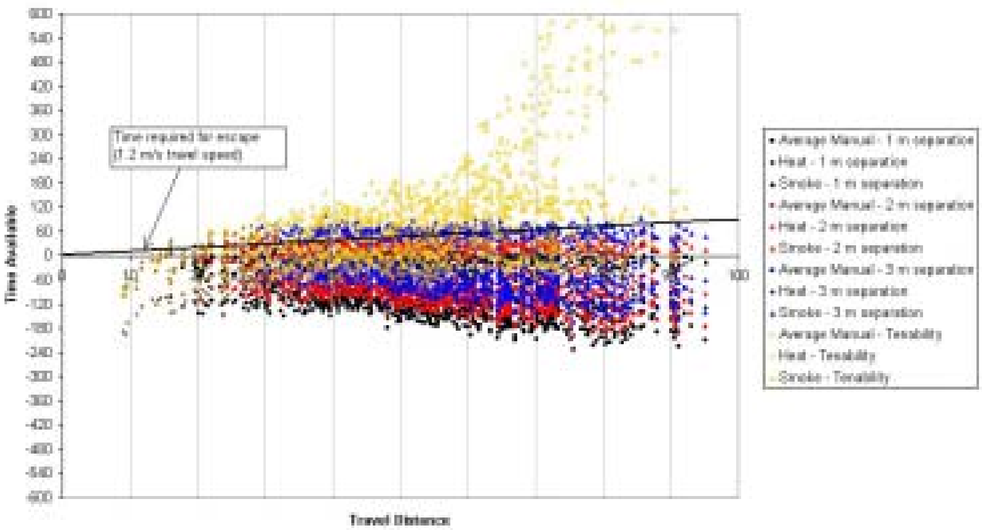

Figure 4.62 : Available Escape Time from Work Environment – Y5.4/21 Sofa Fire

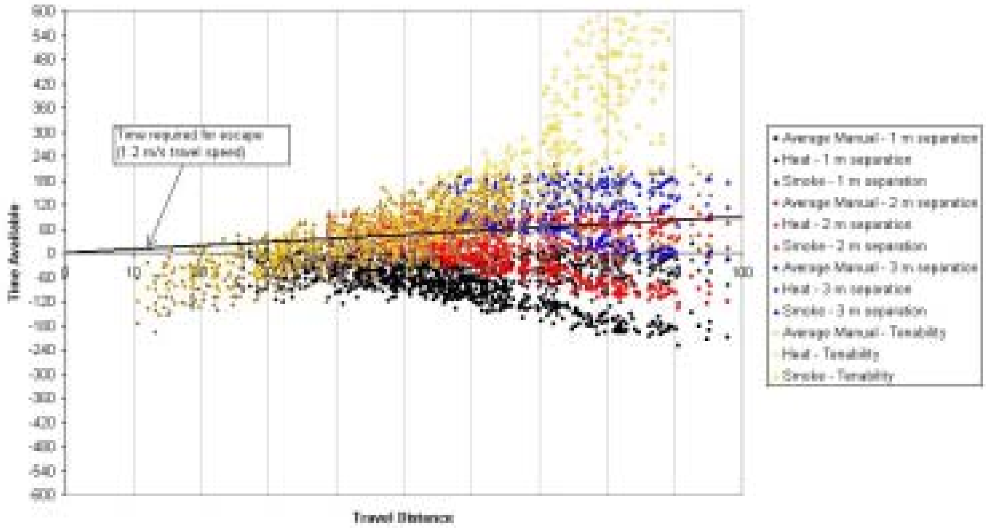

Figure 4.63 : Available Escape Time from Work Environment – Loveseat Fire

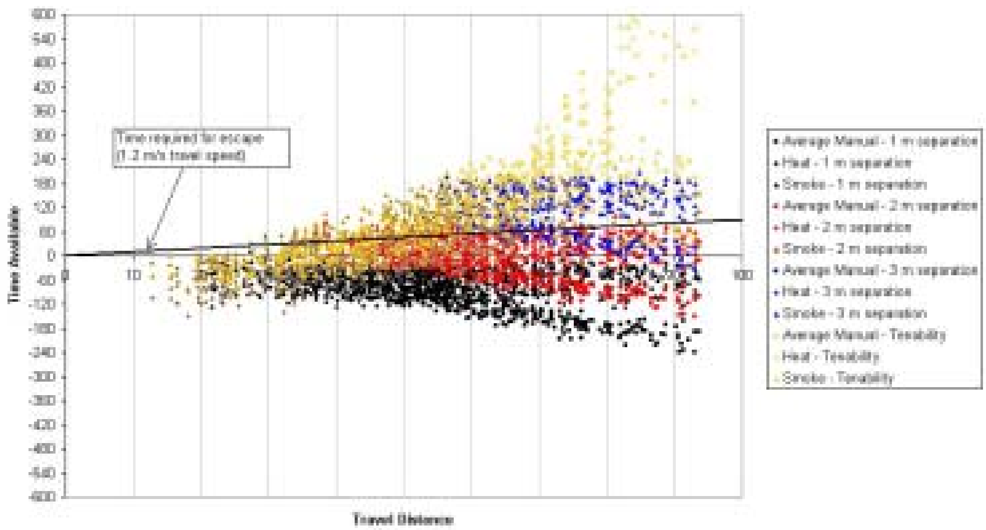

Figure 4.64 : Available Escape Time from Work Environment – Sofa Fire

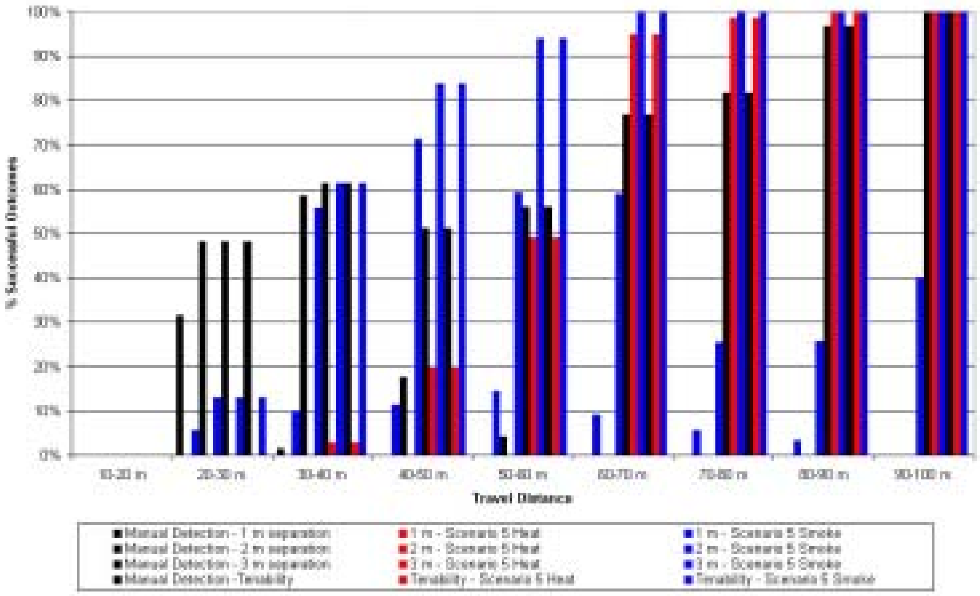

Figure 4.65 : Work Environment Egress Scenario Outcome Comparison – Y5.0/14 Stackable Chair Fire

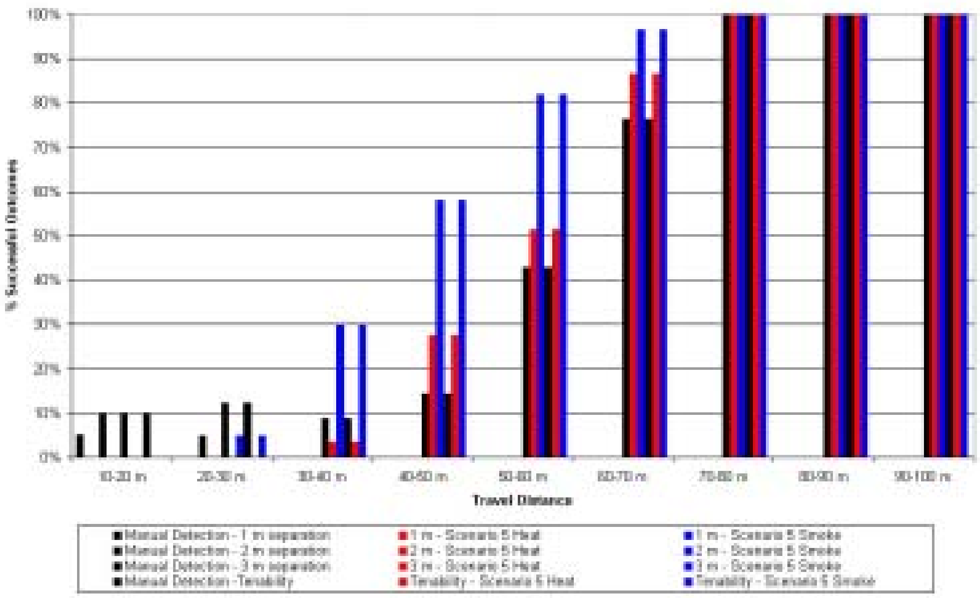

Figure 4.66 : Work Environment Egress Scenario Outcome Comparison – Y5.3/10 Chair Fire

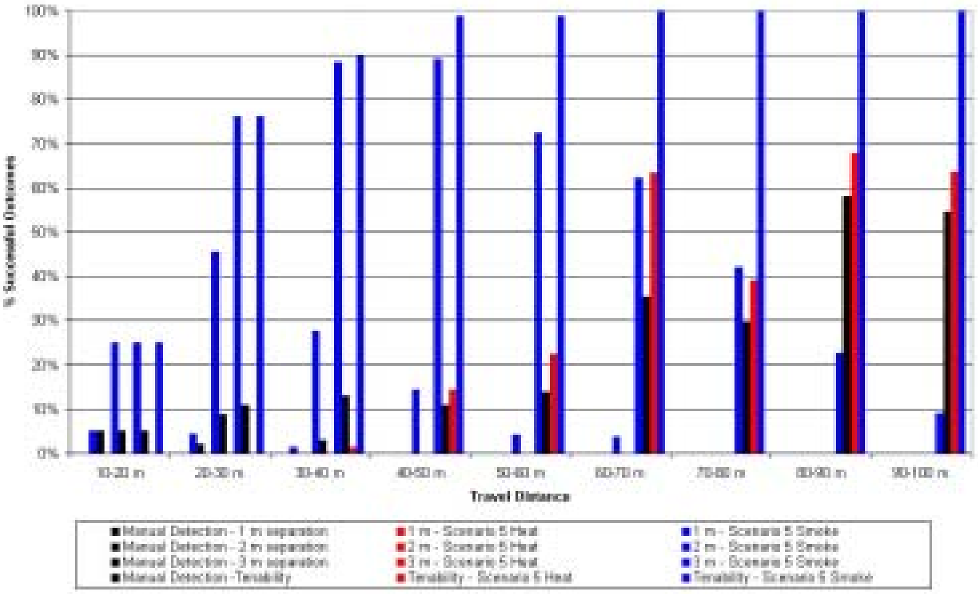

Figure 4.67 : Work Environment Egress Scenario Outcome Comparison – Y5.4/21 Sofa Fire

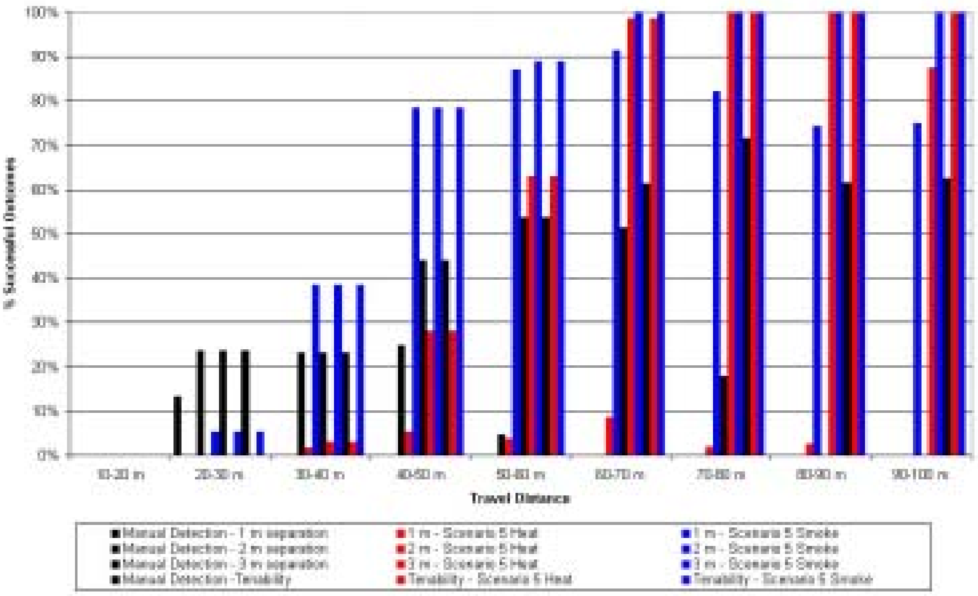

Figure 4.68 : Work Environment Egress Scenario Outcome Comparison – Loveseat Fire

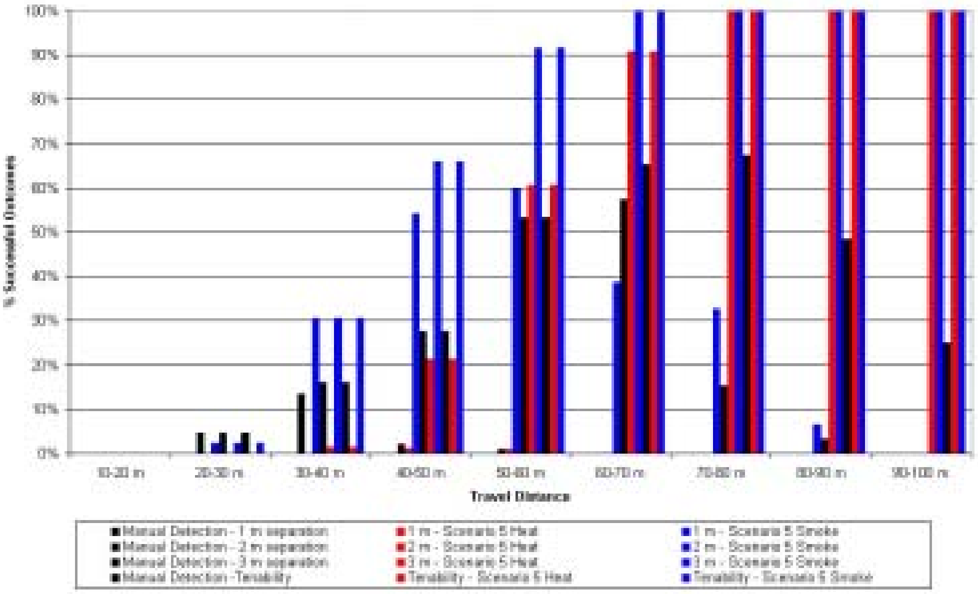

Figure 4.69 : Work Environment Egress Scenario Outcome Comparison – Sofa Fire

When sprinklers are provided, these still tend to respond too late to give any successful egress scenarios in the smaller firecells, particularly where the travel distance is less than 30 m. There is relatively little variation between Figure 4.70 through Figure 4.74, each having a similar spread of results, with no particularly unusual features.

The success rates of these scenarios are shown in Figure 4.75 through Figure 4.79. Here the differences are slightly more marked. As noted in previous analyses, manual detection and smoke detection both occur before sprinkler activation. This is most noticeable in the mid-size firecells. In the larger firecells (60 m travel distance and up) there is little effect, and in the small firecells (up to 20 to 30 m travel distance), sprinkler operation is too late to sufficiently delay the loss of tenability (as observed in the standard t^2 fast fire growth rate earlier).

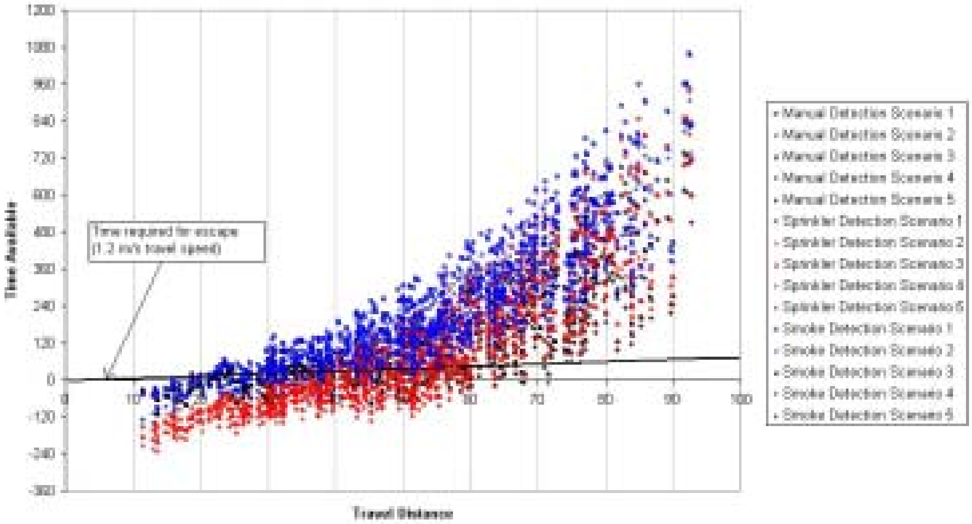

Figure 4.70 : Available Escape Time from Sprinkler Protected Work Environment – Y5.0/14 Stackable Chair Fire

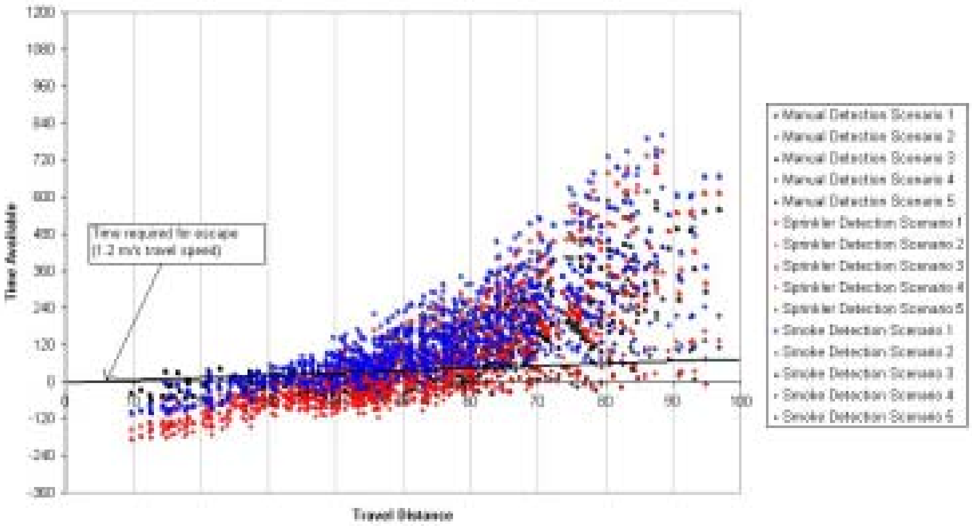

Figure 4.71 : Available Escape Time from Sprinkler Protected Work Environment – Y5.3/10 Chair Fire

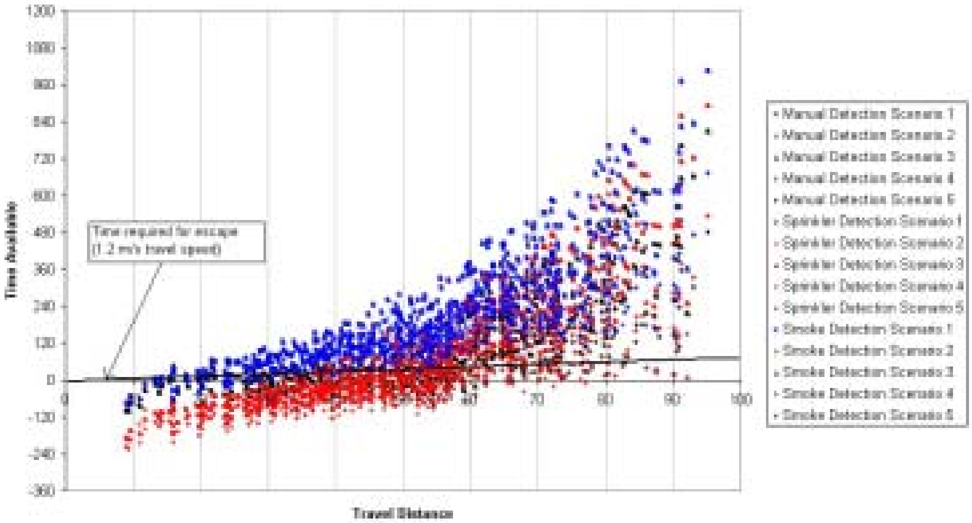

Figure 4.72 : Available Escape Time from Sprinkler Protected Work Environment – Y5.4/21 Sofa Fire

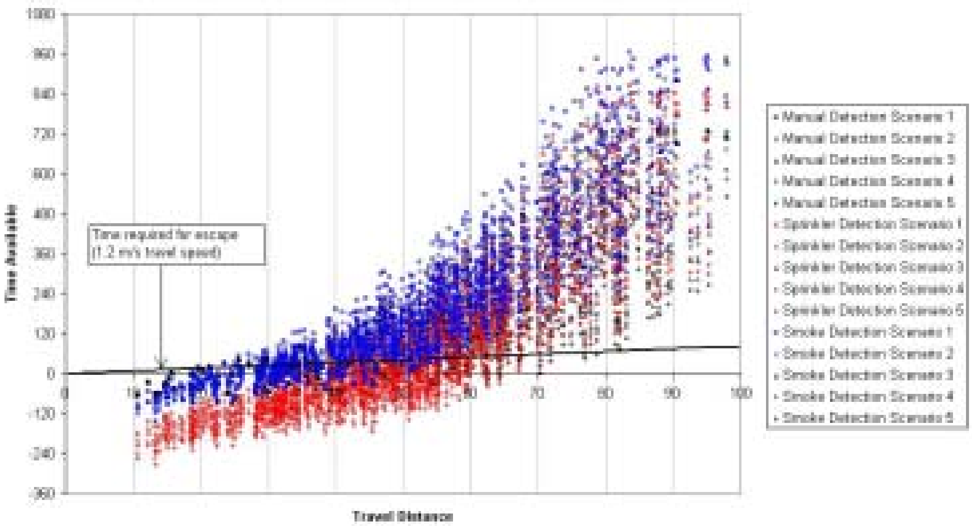

Figure 4.73 : Available Escape Time from Sprinkler Protected Work Environment – Loveseat Fire

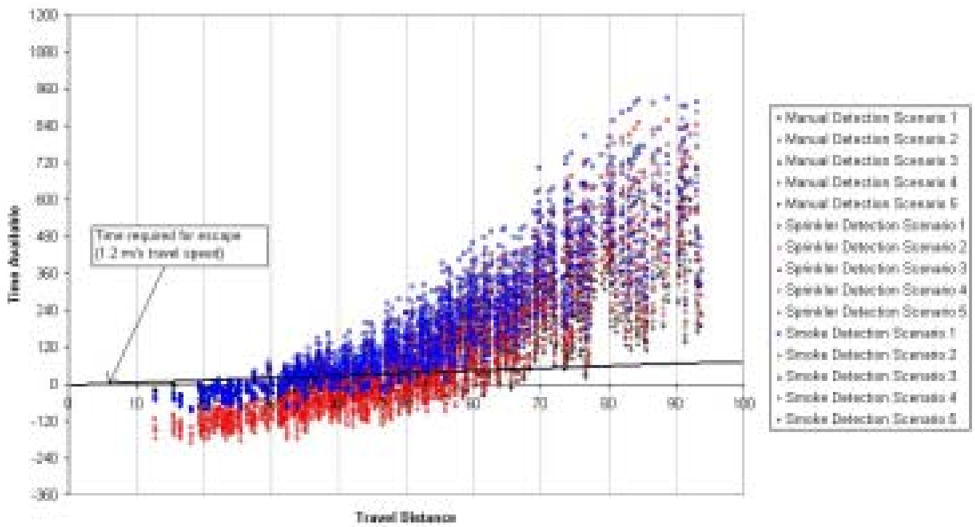

Figure 4.74 : Available Escape Time from Sprinkler Protected Work Environment – Sofa Fire

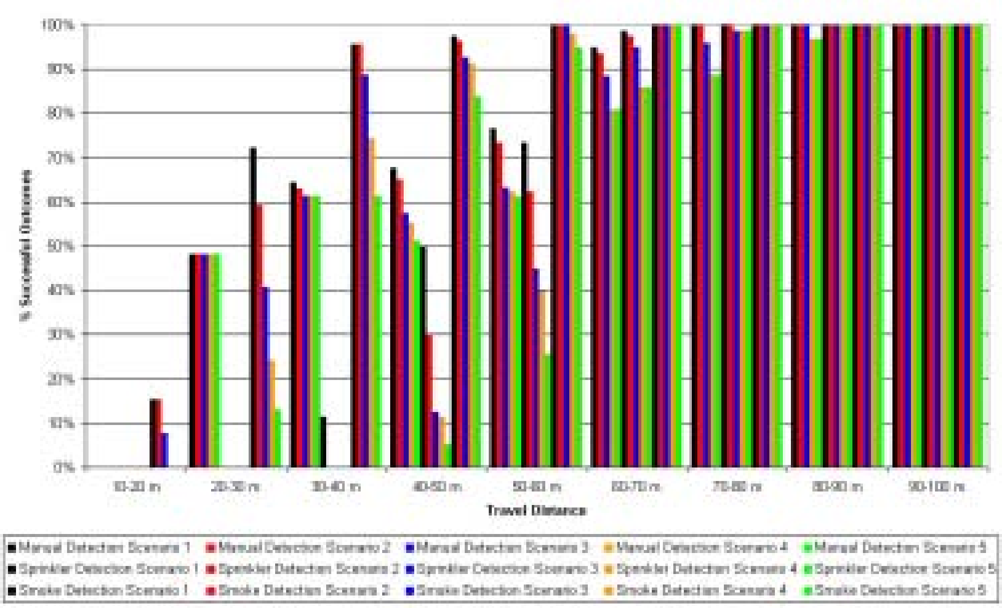

Figure 4.75 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Y5.0/14 Stackable Chair Fire

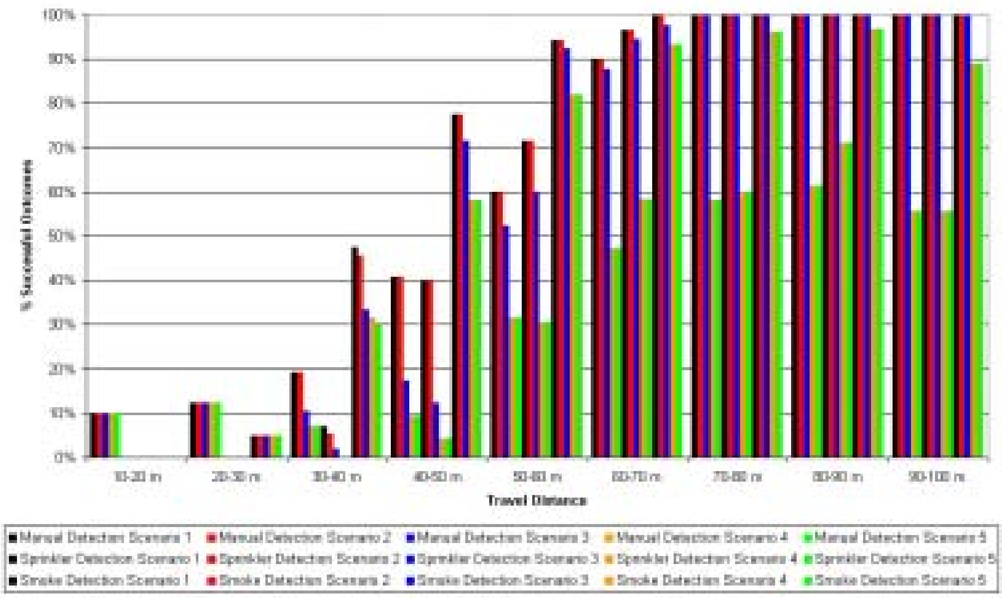

Figure 4.76 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Y5.3/10 Chair Fire

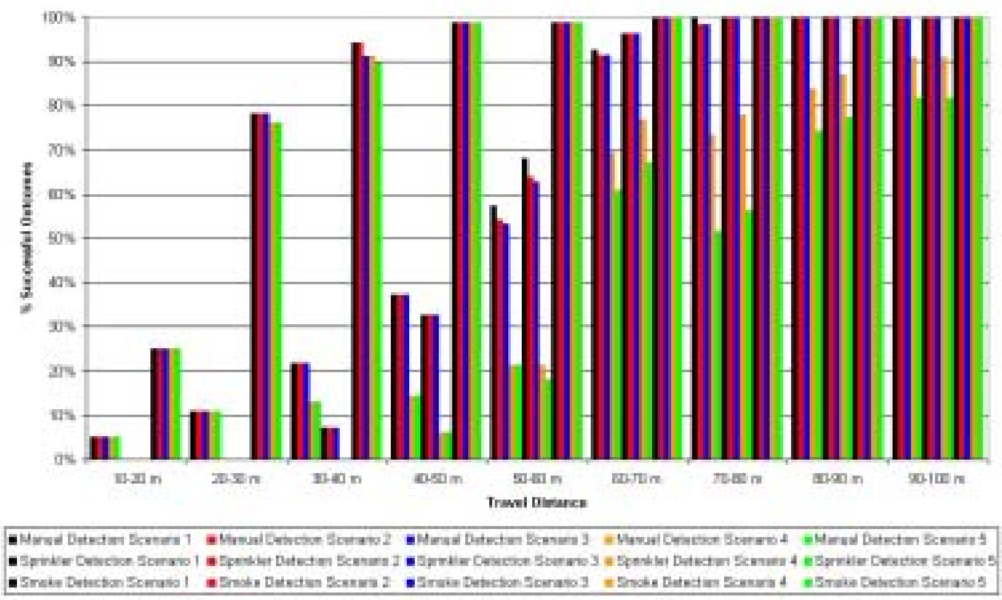

Figure 4.77 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Y5.4/21 Sofa Fire

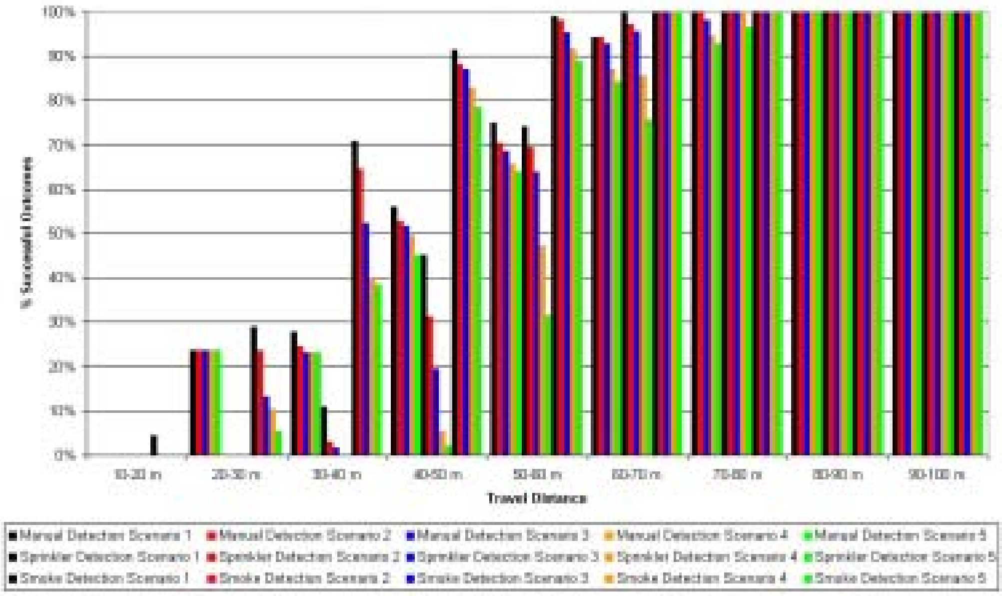

Figure 4.78 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Loveseat Fire

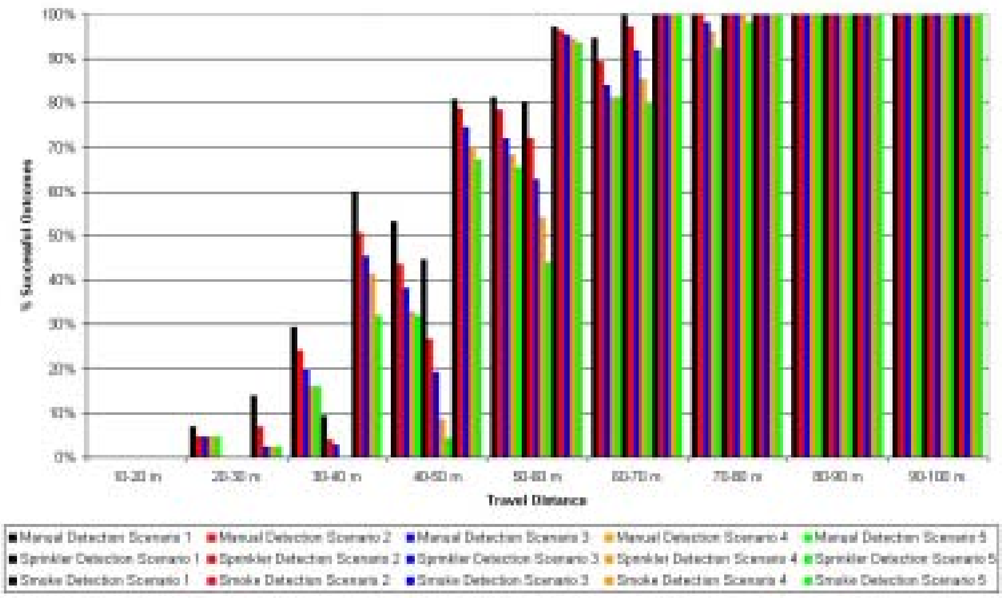

Figure 4.79 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Sofa Fire

When these fires are considered in a crowd environment (mobile, such as retail, or seated, such as a bar or restaurant), and the escape scenarios are considered (see Appendices, Section 12), it can be seen that the increased *pre-movement* time significantly reduces the number of successful scenarios. Although similar separation requirements to those noted in the office *occupancy* remain applicable, the loss of tenability causes many failures. When sprinklers are provided, these remain most effective in the large firecells, with tenability typically being lost in the small areas before egress can be completed.

Storage Fires: Y3.1/13, Y3.3/13 and Small Dresser

The remaining fires to be considered are of a storage nature, being a wardrobe, a pair of bookcases, and a small dresser. These could typically occur in any *occupancy*. The limiting times for various travel speeds and separation distances are given in Table 4.8.

Fire Description	1.2 m/s travel speed (work)			0.8 m/s travel speed (crowd)		
	1 m 536 kW	2 m 1607 kW	3 m 3069 kW	1 m 295 kW	2 m 1031 kW	3 m 2173 kW
Y3.1/13 Wardrobe	66 sec	90 sec	100 sec	65 sec	75 sec	95 sec
Y3.3/13 Bookcase	245 sec	305 sec	Not reached	215 sec	270 sec	Not reached
Small Dresser	300 sec	413 sec	Not reached	240 sec	375 sec	Not reached

Table 4.8 : Storage Item Fires - Limiting Times for Passing Fires

A comparison of the heat release rates for these items (refer Figure 4.29, Figure 4.30, and Figure 4.35) indicates significant differences in both the growth rate of the fire and the size of the peak heat release rate. The wardrobe fire is the most severe fire of the three, reaching a peak heat release rate of over 6000 kW less than 150 seconds after ignition. The bookcase arrangement peaks at just over 1500 kW, reached in approximately 300 seconds, and the small dresser reaches a similar peak in just over 400 seconds.

Given the fast growth rate and high peak heat release rate of the wardrobe fire, it is un-surprising that like the ultra-fast t² fire, there are few successful scenarios apparent in Figure 4.80, as confirmed in Figure 4.83.

The slower growth rates of the bookcase and dresser fires mean that there is a significant improvement in the success rates (see Figure 4.81 and Figure 4.82). Both of these fires will permit egress up to approximately 2 m from the fire, even at the peak heat release rate. This is confirmed in Figure 4.84 and Figure 4.85 where it can be seen that obstruction by the fire gradually affects egress as travel distance increases, with the maximum separation required being 2 m.

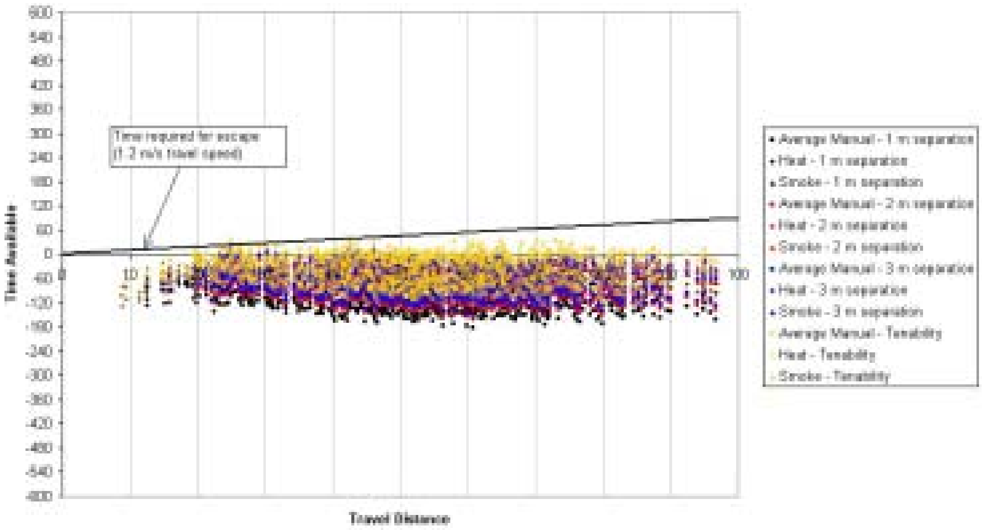

Figure 4.80 : Available Escape Time from Work Environment – Y3.1/13 Wardrobe Fire

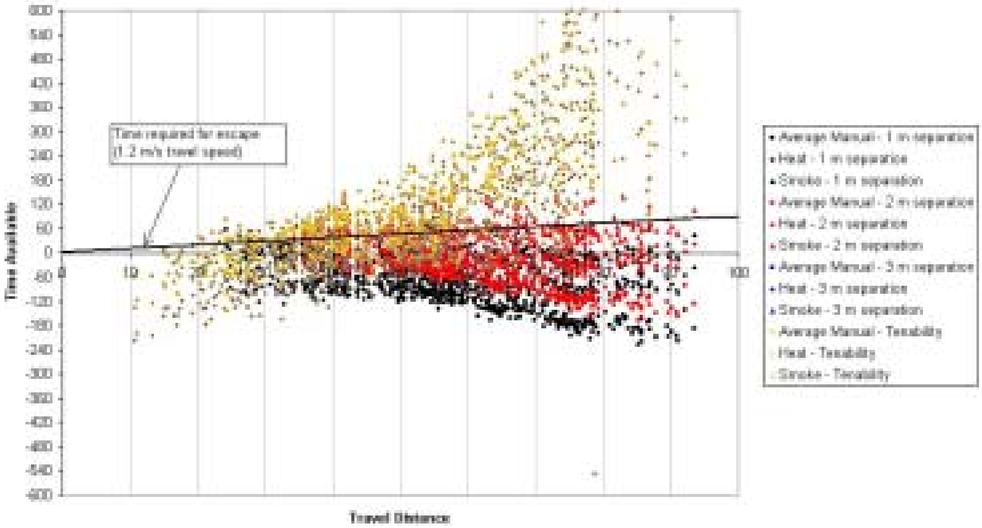

Figure 4.81 : Available Escape Time from Work Environment – Y3.3/13 Bookcase Fire

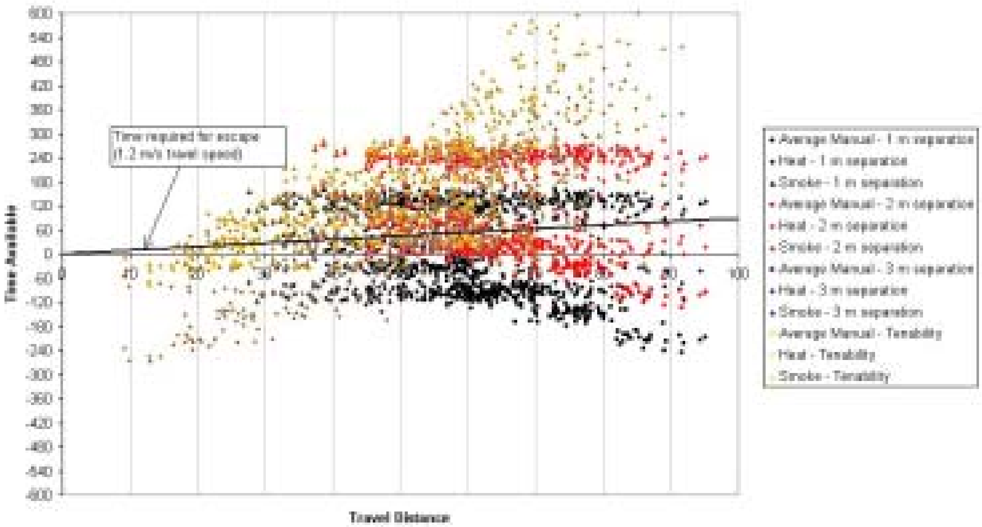

Figure 4.82 : Available Escape Time from Work Environment – Small Dresser Fire

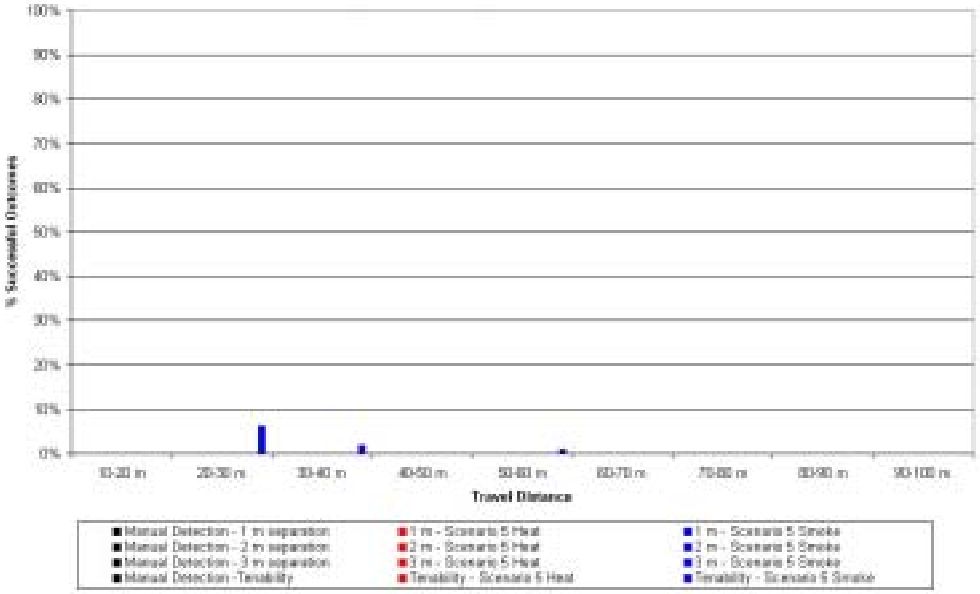

Figure 4.83 : Work Environment Egress Scenario Outcome Comparison – Y3.1/13 Wardrobe Fire

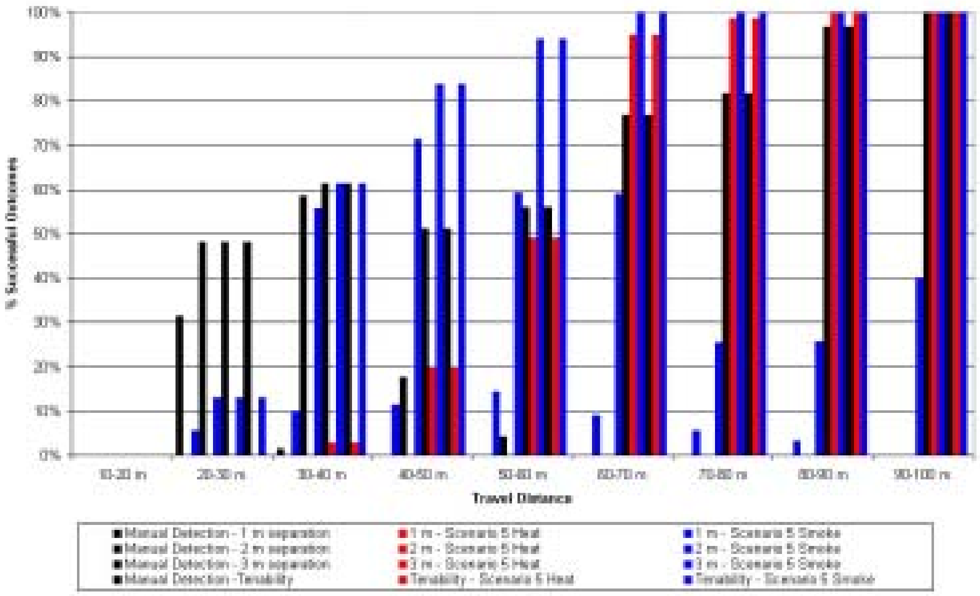

Figure 4.84 : Work Environment Egress Scenario Outcome Comparison – Y3.3/13 Bookcase Fire

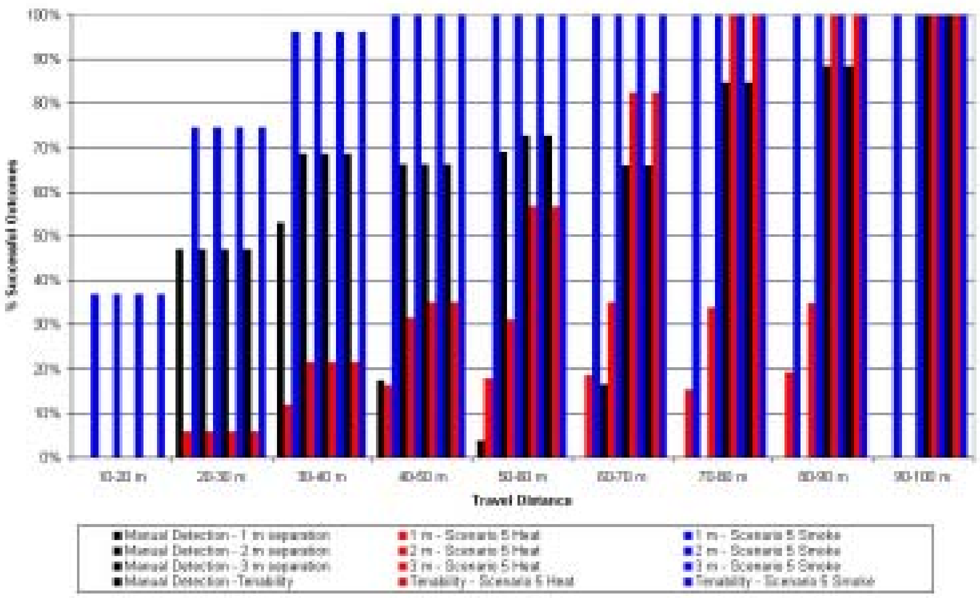

Figure 4.85 : Work Environment Egress Scenario Outcome Comparison - Small Dresser Fire

When the wardrobe fire is placed in a sprinkler protected environment (see Figure 4.86), the fire growth rate is still such that by the time the sprinklers control the fire, it is relatively large, and the smoke produced causes tenability to be lost comparatively quickly.

Figure 4.89 confirms this, and also indicates that when sprinklers are installed at the maximum compliant spaces, tenability is not maintained long enough to allow any successful egress scenarios.

For the other fires, sprinklers operate earlier, and are more effective in controlling the smoke production. As for the standard medium t^2 fire there is a reasonable chance of successful egress after manual detection where the firecell has a travel distance longer than 30-40 m.

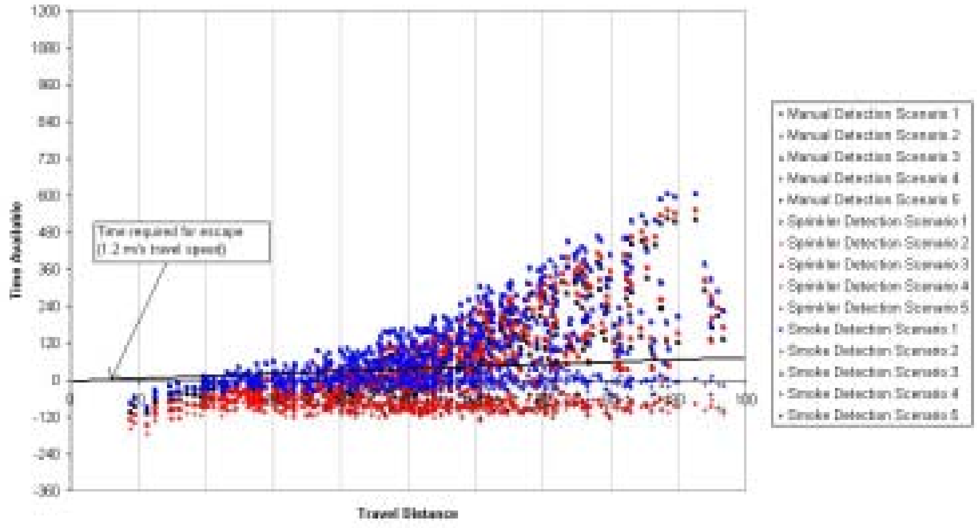

Figure 4.86 : Available Escape Time from Sprinkler Protected Work Environment – Y3.1/13 Wardrobe Fire

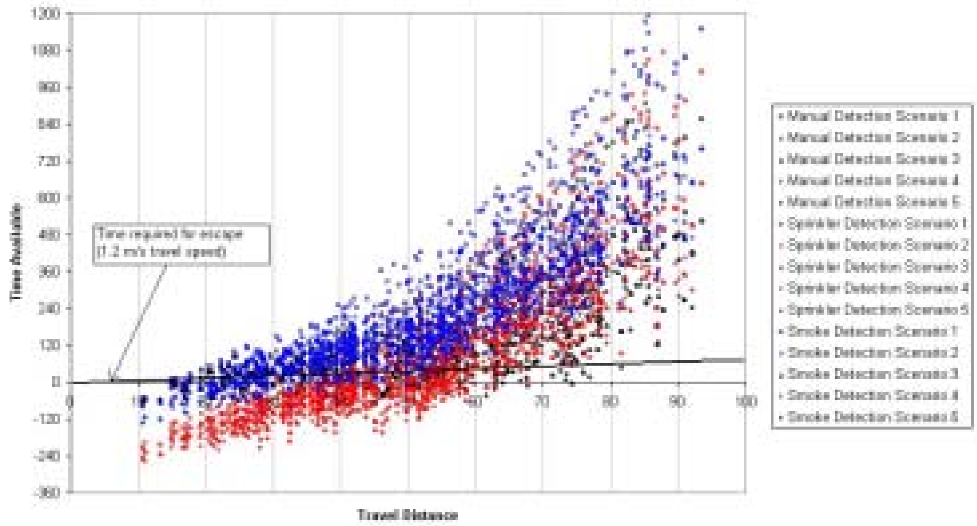

Figure 4.87 : Available Escape Time from Sprinkler Protected Work Environment – Y3.3/13 Bookcase Fire

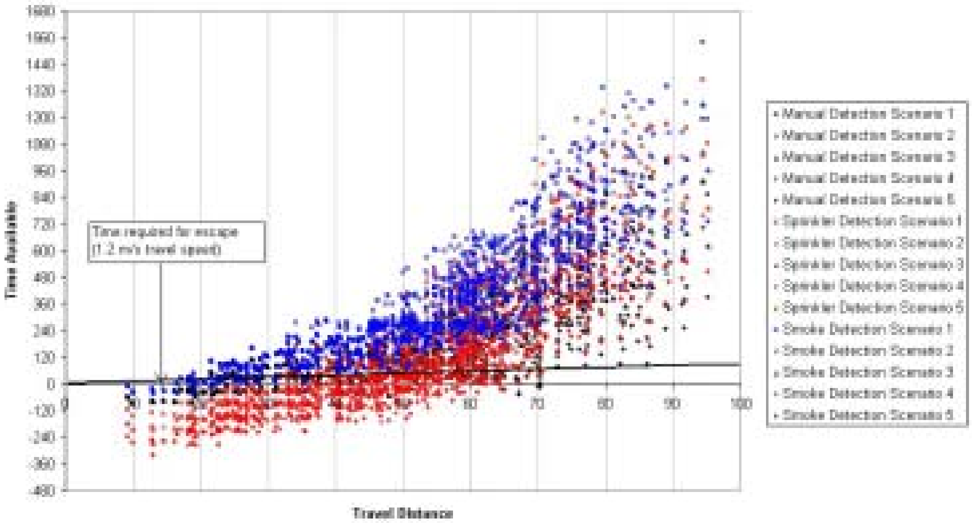

Figure 4.88 : Available Escape Time from Sprinkler Protected Work Environment – Small Dresser Fire

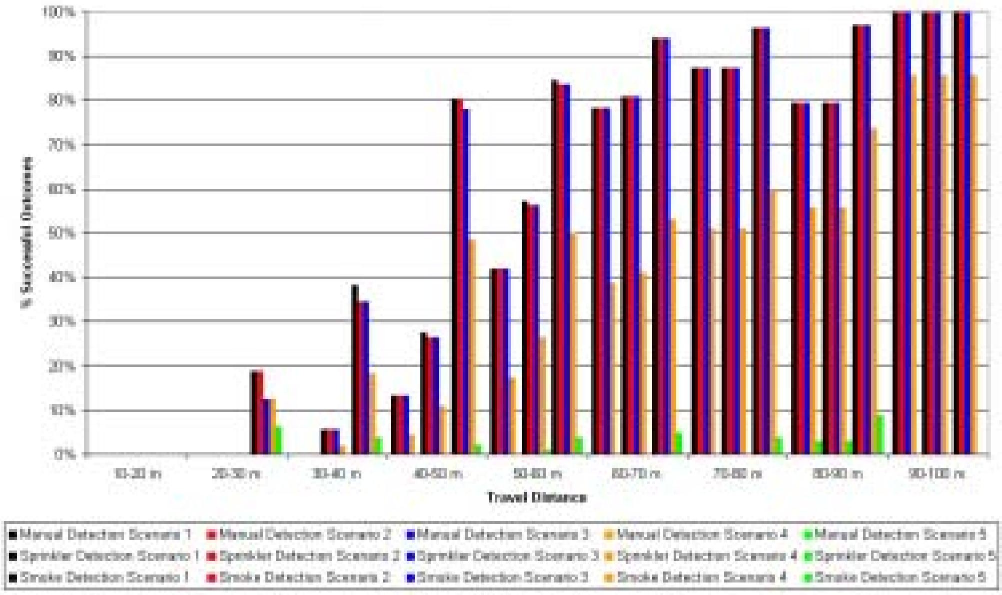

Figure 4.89 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Y3.1/13 Wardrobe Fire

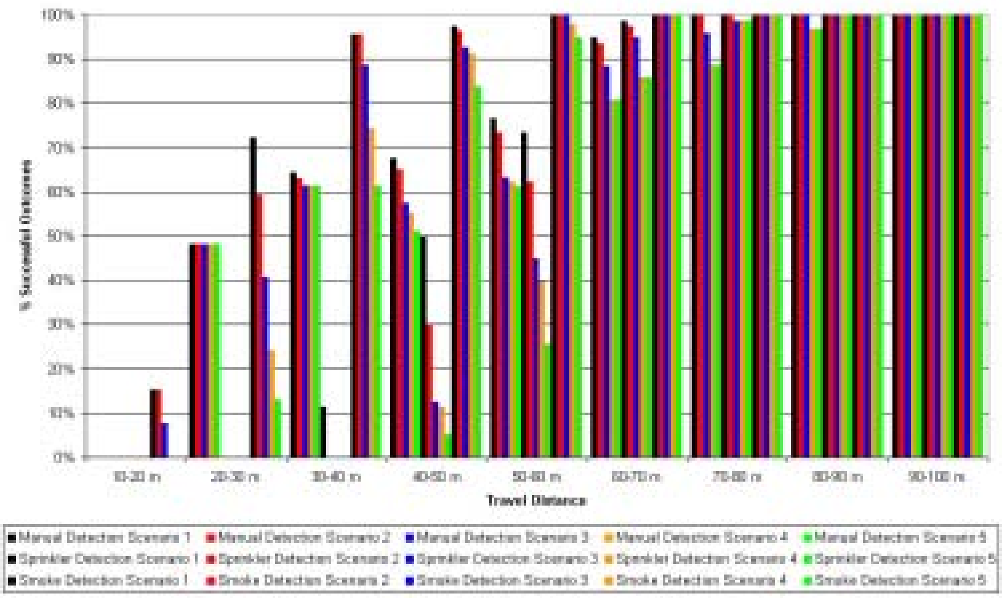

Figure 4.90 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Y3.3/13 Bookcase Fire

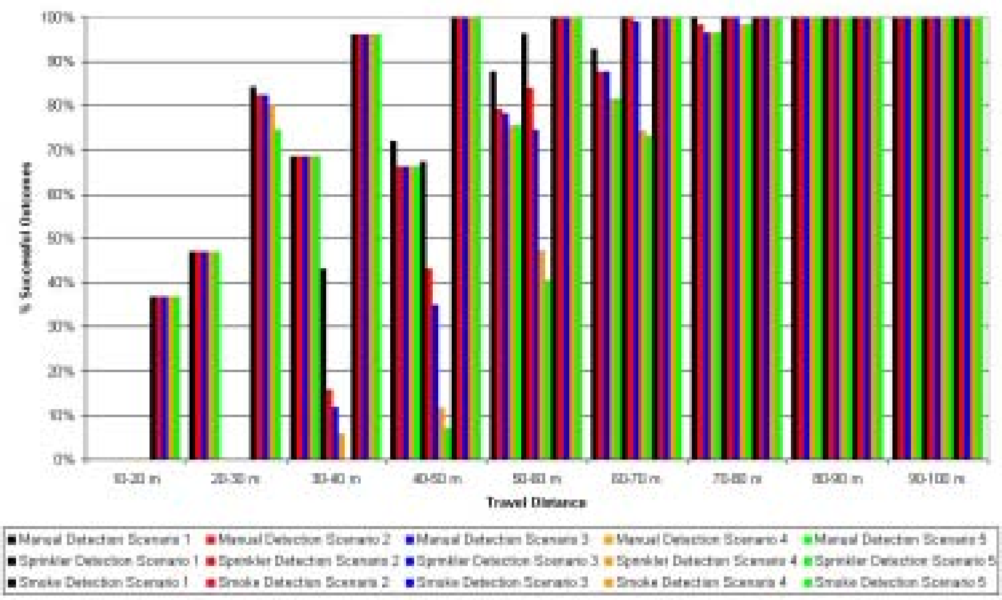

Figure 4.91 : Work Environment Sprinkler Protection Egress Scenario Outcome Comparison – Small Dresser Fire

When these item fires are placed in a crowd environment, similar trends can be seen. There are no successful egress scenarios for either *occupancy* during a wardrobe fire. There are some, but few, successful egress scenarios from the bookcase fire, and as noted earlier, these are more plentiful in the larger firecells. The small dresser fire permits an even greater number of successful egress outcomes, particularly in small firecells.

Similarly, when sprinklers are provided, the same trends can be seen:

- No successful outcomes for compliant sprinklers and a wardrobe fire.
- In the two other fires, larger firecells give the best tenability times, and hence better success rates.

4.2.2 Summary of Results of Item Fires

When a review of the item fires analysed above is made, and the type of *occupancies* in which the items are likely to be found (or conversely, the types of items likely to be found in the *occupancies* considered), the results are summarised in Table 4.9, Table 4.10, and Table 4.11.

Item Fire	Manual Detection Results	Heat Detection Results	Smoke Detection Results	Sprinkler Protection Results
Y0/21 Office Workstation	The initial smouldering period produces enough smoke for early manual detection. If travel distance < 10 m, tenability inadequate. 20-40 m is mostly successful. >40 m virtually all successful. No obstruction problems.	Very few successful outcomes – only when travel distance > 80 m, best rate when > 90 m, and a 3 m separation required.	Similar or better results to manual detection, particularly when travel distance > 30 m. No obstruction problems.	Smoke detection gives a few successes at < 20 m, and provides best warning where travel distance > 50 m. Response to sprinkler activation only successful in large firecell where travel distance > 90 m.
Y0/22 Office Workstation	Some success where travel distance < 10 m. Not acceptable success rate (~90% success) until > 50 m. No obstruction problems.	Some success when > 50 m, but not >90% success until travel distance > 60 m. No obstruction problems	Activates later than manual detection when travel distance < 30 m. Travel distances > 40 m give acceptable success rate. No obstruction problems.	Manual detection gives a few successes at < 20 m travel distance, at greater distances smoke detection gives similar success rate. Acceptable success when smoke detection provided if travel distance > 50 m. Without smoke detection, need > 60 m travel distance. Response to sprinkler activation requires > 70 m travel distance.

2 Panel Workstation	Success rate not acceptable til travel distance > 50 m. 3 m separation required for success.	Reasonable success rate when travel distance > 50 m. 3 m separation required.	Some success at travel distances < 20 m so activates earlier than manual in this situation. Up to 60 m travel distance, 1 m separation ok, for further travel distance, need 2 m separation.	Smoke detection gives a few successes for travel distance < 20 m, and is generally faster than manual. Reasonable success rate when travel distance > 50 m for manual, or 30 m for smoke detection, or 60 m for response to sprinkler activation.
3 Panel Workstation	Not acceptable success rate til travel distance > 40 m, and separation is 3 m or more. At lesser travel distances, obstruction is less of a problem, but tenability causes failure.	Reasonable success when travel distance > 20 m, but not acceptable til travel distance > 40 m. 2 m separation is adequate for most travel distances.	Some success at < 20 m travel distance. Acceptable success rates at travel distance > 30 m. 2 m separation required for most travel distances.	Smoke detection allows a few successful outcomes when travel distance < 20 m, and generally gives best results for all travel distances. Acceptable success rate for smoke detection reached when travel distance > 30 m. If only manual detection, need > 60 m travel distance, if responding to sprinkler activation, need > 70 m.

Y5.0/14 Stackable Chairs	No success til travel distance > 30 m, and not acceptable success rate til travel distance > 80 m. 3 m separation required.	Some success when travel distances > 40 m, but not acceptable rates til travel distance > 60 m. 3 m separation required.	Some success when travel distance < 30 m. Not acceptable success rates til travel distance > 50 m. 3 m separation required.	Smoke detection typically occurs before manual detection. No successful outcomes less than 20 m travel distances. Smoke detectors give acceptable rates when travel distance > 40 m. Manual and sprinkler detection give acceptable rates when travel distance > 60 m.
Y5.3/10 Easy Chair	Some success for travel distances < 20 m, and no obstruction effect noticeable at this distance. With travel distances between 20 and 30 m, separation of 2 m required, and above that need 3 m. Acceptable success rate not reached for travel distances less than 60 m.	Some success when travel distance > 40 m. Acceptable success when travel distance > 60 m. 3 m separation required.	Some success when travel distance < 30 m. Acceptable success when travel distance > 60 m. 3 m separation required.	Some success for manual detection, but not smoke detection, with travel distances < 20 m. Manual detection is sooner until travel distance exceeds 30 m. Smoke detection allows adequate success rate when travel distance > 60 m. Manual and sprinkler detection give adequate success rate when travel distance > 70 m.

Y5.4/21 Sofa	Some success when travel distance < 20 m, but 2 m separation required. Acceptable Levels of egress success not reached at any travel distance.	No successful outcomes for travel distance < 40 m. 3 m separation required for success, but acceptable rates not reached.	Some success for travel distance < 20 m, acceptable success where travel distance > 30 m. 3 m separation required, with greater separation at > 50 m travel distance.	Some smoke detection, but not manual success at < 20 m travel distance. Smoke detection results in acceptable results at > 50 m travel distances. Manual detection acceptable at > 60 m travel.
Loveseat	Some success at travel distances < 30 m. Need 50 m travel distance and 2 m separation for acceptable rate.	60 m travel distance required for acceptable success rate, with 3 m separation.	Some success < 30 m travel distance, acceptable success rate > 50 m travel distance. 2 m separation required.	Both manual and smoke detection allow some success < 30 m. Smoke response earlier when travel distance > 30 m. Manual response gives acceptable success rate at > 60 m, smoke detection requires > 50 m.
Sofa	Some success < 30 m travel distance, 2 m separation required at this distance. Separation increases to > 3 m as distance increases. Acceptable success rates not met.	Some success at > 40 m, and 3 m separation. Acceptable rates not reached.	Some success at < 30 m travel distance with 1 m separation. Acceptable success rates at > 50 m but fire can obstruct if within 3 m of the escape path.	Both manual and smoke detection have some success at travel distances 20-30 m. Acceptable rates at travel distance > 50 m for smoke detection, > 60 m for manual detection.

Y3.1/13 Wardrobe	No successful outcomes	No successful outcomes	No successful outcomes	Sprinkler heads need to be at closer than "compliant" spacings to control fire to permit evacuation. Acceptable success rates at > 60 m travel distance for smoke detection, 70 m for manual detection.
Y3.3/13 Bookcase	Some success at 20-30 m travel distance. Fires closer than 2 m start to control egress when travel distance > 50 m, and 3 m separation required for acceptable rates.	3 m separation and > 60 m travel distance required for acceptable success rate.	No faster than manual detection when travel distance < 40 m. Acceptable success rate when travel distance > 40 m, and 2 m separation achieved.	Some smoke detection success at < 20 m travel distances. Acceptable success for smoke detection at > 50 m, and for manual detection at > 60 m.
Small dresser	Some success above 20 m travel distance. Acceptable success rate when travel distance > 70 m. 3 m separation needed at that travel distance, though shorter travel distances are less affected by obstruction.	Acceptable success rate at > 70 m travel distance and 3 m separation. When travel distance < 50 m, obstruction doesn't occur when fire more than 2 m away.	Some success when travel distance < 20 m. Typically faster than manual detection. Acceptable success rate at travel distance > 30, no fire obstruction for 1 m separation.	Some smoke detector success for < 20 m travel distance, and smoke detection occurs before manual. Acceptable rates at smoke detection > 40 m travel distance, and > 60 m for manual detection.

Table 4.9 : Work Environment Fires

Item Fire and Environment	Manual Detection	Heat Detection	Smoke Detection	Sprinkler Protection
Y0/22 Office Furniture	Some success where travel distance < 20 m, but not acceptable rate til travel distance > 60 m. 2 m separation required to prevent obstruction for travel distances > 30 m.	Acceptable rate when travel distance > 60 m, 2 m separation.	Some success at approx 30 m travel distance, but not acceptable rate til > 50 m travel distance and 2 m separation.	Manual detection gives some success below 20 m travel distance. Smoke detection earlier than manual where the travel distance > 40 m, otherwise, manual detection first. Acceptable result levels for smoke detection for travel distances > 50 m, manual detection > 60 m travel.
Y5.0/14 Stackable Chairs	No success < 30 m travel distance. Not acceptable til > 80 m travel distance and > 3 m separation.	No success < 40 m travel distance. Not acceptable til > 60 m travel distance and > 3 m separation	Some success < 30 m travel distance, but not acceptable til > 60 m travel distance and > 3 m separation.	Smoke detection occurs before manual detection. Smoke detection acceptable where > 60 m travel distance, manual detection at > 70 m travel distance, sprinkler activation similar to manual detection in larger firecells

Y5.3/10 Easy Chair	Some success < 20 m where separation > 2 m. Not acceptable til travel distance > 80 m and separation > 3 m.	No success til > 40 m travel distance, not acceptable til > 70 m travel and > 3 m separation.	No success til > 30 m travel, and not acceptable til > 60 m travel and > 3 m separation.	Smoke detection before manual in small firecells. Smoke detection gives acceptable results where travel distance > 60 m. Manual detection acceptable where travel distance > 70 m, but need closer sprinkler spacings.
Y5.4/21 Sofa	Some success possible, but doesn't reach acceptable levels	Some success possible, but doesn't reach acceptable levels.	Some success for travel distances < 20 m and separation > 1 m, but not acceptable til travel distance > 60 m and separation of 3 m.	Smoke detection before manual in smaller firecells. Smoke detection gives acceptable results where the travel distance > 60 m. Manual detection results acceptable for travel distance > 70 but only for closer spaced sprinklers.
Loveseat	Some success where travel distance > 30 m, but doesn't reach acceptable levels	Acceptable success rates for travel distance > 70 m and more than 3 m separation.	Some success > 30 m. Acceptable success rates for travel distance > 60 m and separation > 3 m.	Smoke detectors activate before manual in small firecells. Smoke detectors give acceptable results for travel distances > 60 m, and manual detection > 70 m.

Sofa	Some success at 30 m travel distance and > 3 m separation, but doesn't reach acceptable success levels.	Acceptable success rates where travel distance > 70 m and separation > 3 m.	Some success at > 30 m travel distance and 3 m separation. Acceptable success rates require > 60 m travel distance with 3 m separation.	Smoke detectors activate first in small firecells. Smoke detector results acceptable for travel distances > 60 m, manual detection is acceptable for travel distances > 70 m.
Y3.1/13 Wardrobe	No successful outcomes	No successful outcomes	No successful outcomes	Sprinkler heads need to be at closer than "compliant" spacings to control fire to permit evacuation. Up to 80% success rate possible, but no higher.
Y3.3/13 Bookcase	Some success at 20-30 m travel distance. 80 m travel distance and 3 m separation required for acceptable success rates.	3 m separation and > 70 m travel distance required for acceptable success rate.	Some success at > 20 m travel distance. At 30 m travel distance, 2 m separation required. Acceptable success rates at > 60 m travel distance and 3 m separation.	Some smoke detection success at > 20 m travel distances, as does manual. Acceptable success for smoke detection at > 50 m, and for manual detection at > 70 m.
Small dresser	Some success above 20 m travel distance. Acceptable success rate when travel distance > 70 m. 3 m separation.	Acceptable success rate at > 70 m travel distance and 3 m separation.	Some success when travel distance < 20 m. Typically faster than manual detection. Acceptable success rate at travel distance > 30, 2 m separation required.	No smoke detector success for < 20 m travel distance, but smoke detection occurs before manual. Acceptable rates at smoke detection > 40 m travel distance, and > 70 m for manual detection.

Table 4.10 : Mobile Crowd Environment Fires

Item Fire and Environment	Manual Detection	Heat Detection	Smoke Detection	Sprinkler Protection
Y0/22 Office Furniture	Little success for travel distances > 30 m, and fire separation to escape route of 3 m or less. Acceptable rates at travel distance > 60 m, but not if fire 3 m or closer to escape route.	Acceptable when travel distance > 60 m and fire further than 3 m from escape route.	Acceptable when travel distance > 50 m and fire further than 3 m from escape route.	Smoke and manual response at similar times in smaller firecells. Smoke detection gives acceptable results when travel distance > 50 m, manual detection requires > 60 m.
Y5.0/14 Stackable Chairs	No successful outcomes with travel distance < 30 m. Acceptable level of success where travel distance > 90 m and separation > 3 m.	No success < 50 m travel distance. Acceptable level of success where travel distance > 90 m and separation > 3 m.	No success < 30 m travel distance. Acceptable levels when travel distance > 60 m and 3 m separation provided.	Smoke detection before manual in small firecells. Smoke detection gives acceptable rate at > 70 m, manual at > 80 m.
Y5.3/10 Easy Chair	No success for travel distances < 40 m. Acceptable success levels reached when travel distance > 70 m and separation > 3 m.	Acceptable level of success when travel distance > 70 m and separation > 3 m.	Little success where travel distance < 40 m. Not acceptable til travel distance > 70 m. > 3 m separation required.	Smoke detection before manual detection. Closer spaced sprinklers required for acceptable success rate, at travel distance > 60 m for smoke detection and > 70 m for manual detection.
Y5.4/21 Sofa	No success for travel distance < 60 m. Acceptable levels not reached. Obstruction when fire within 3 m of escape route.	Some success at 30 m travel distance. Acceptable Levels not reached. Obstruction when fire within 3 m of escape route.	Some success at < 20 m travel distance, but acceptable success levels not reached. Obstruction when fire within 3 m of escape route.	Smoke detection before manual detection. Smoke detection gives acceptable success rate when travel distance > 60 m, manual detection when travel distance > 80 m.
Loveseat	Some success at 30 m travel distance. Acceptable levels	Some success at 50 m travel distances, but acceptable	Some success at 30 m travel distance. Acceptable success	Smoke detection operates before manual detection.

	not reached. Fire tends to obstruct if within 3 m of route.	success rates not reached. Fire tends to obstruct if within 3 m of route.	levels at travel distances > 70 m and > 3 m separation.	Smoke detection gives acceptable success rate when travel distance > 60 m, manual when travel distance > 70 m.
Sofa	Some success at 40 m travel distances and 3 m separations. Acceptable success rate not reached.	Some success at 40 m travel distance and 3 m separations. Acceptable success rate not reached.	Some success at 30 m travel distance. Acceptable success rate reached at travel distance > 70 m and separation > 3 m.	Smoke detection operates before manual detection. Smoke detection gives acceptable success rate for travel distance > 60 m, manual detection needs 70 m.
Y3.1/13 Wardrobe	No successful outcomes	No successful outcomes	No successful outcomes	Sprinkler heads need to be at closer than "compliant" spacings to control fire to permit evacuation. Up to 80% success rate possible, but no higher.
Y3.3/13 Bookcase	Some success at 20-30 m travel distance. 80 m travel distance and 3 m separation required for acceptable success rates.	3 m separation and > 80 m travel distance required for acceptable success rate.	Some success at > 30 m travel distance. At 30 m travel distance, 3 m separation required. Acceptable success rates at > 60 m travel distance and 3 m separation.	Some smoke detection success at > 20 m travel distances, as does manual. Acceptable success for smoke detection at > 60 m, and for manual detection at > 80 m.

Small dresser	Some success above 20 m travel distance. Acceptable success rate when travel distance > 80 m. 3 m separation.	Acceptable success rate at > 70 m travel distance and 3 m separation.	Some success when travel distance > 20 m. Typically faster than manual detection. Acceptable success rate at travel distance > 50, 2 m separation required.	No smoke detector success for < 20 m travel distance, but smoke detection occurs before manual. Acceptable rates at smoke detection > 50 m travel distance, and > 70 m for manual detection.

Table 4.11 : Seated Crowd Environment Fires

Work Environment

For a working environment, the greatest hazard is from a wardrobe or coat cupboard, which may have an ultra-fast fire growth rate and a very high peak heat release rate. No warning system is adequate to provide sufficient time for egress in such a situation. Where sprinklers are provided, these may not activate fast enough to control such a fire to allow egress, and the arrangement of the wardrobe may also shield the fire from the sprinklers. Only in large firecells where the sprinkler spacing is reduced are there any successful egress outcomes from a wardrobe fire.

The other items found in an office typically have a slower growth rate, a lower peak heat release rate, and often have an initial plateau phase with a low heat release rate. The lower peaks mean that the fire is less likely to obstruct egress, and slower growth rates provide more warning, particularly when preceded by a smouldering phase. The smouldering phase seen in the item fire tests produces adequate smoke for early manual or even smoke detection, without causing loss of tenability too early. For these fires, the continuing trend is for relatively early loss of tenability in small firecells, but generally successful outcomes in larger firecells. When the fire is within 2-3 m of the escape route, it may obstruct it, but this should be balanced against the risk of the fire being in exactly that position, particularly if this is a single critical area in a large firecell.

Of greater concern are the results from chair and sofa fires. These tend to have a relatively fast growth rate, and a sufficiently high peak heat release rate that may obstruct the escape route if the item is within 2-3 of the route.

Usually, manual detection in smaller firecells and smoke detection in larger firecells provides the earliest warning (and therefore most chance of a successful outcome). Heat detection is usually later than manual detection, but is often adequate for longer travel distances.

Where sprinklers are provided, these typically activate too late to be of much benefit in improving the tenability time in small firecells. They will, however, typically limit the fire size so it provides less of an obstruction to egress.

Crowd Environment

Many of the item fires that could occur in an office situation are also relevant to crowd situations. The longer *pre-movement* times associated with this class of *occupancy* mean that the trends noted in the office *occupancy* are continued, but success rates, particularly in small firecells, are significantly reduced.

5 RISK ANALYSIS OF ALTERNATIVE SOLUTIONS

To assess the levels of risk associated with a design compliant with the requirements of the Acceptable Solutions C/AS1 to the New Zealand Building Code, the probability of a successful result for each scenario will be found. These are to be carried out for work and crowd (both mobile and seated) *occupancies*, and are based on the results from the previous section for the relevant item fires. The risk levels, and probability of success will be assessed for the permitted travel distances, as determined by the detection and/or suppression systems provided.

First, consider an open plan office. Where no detectors are provided, the maximum permissible *dead end open path* travel distance is 24 m. When heat detectors are provided, this distance is permitted to increase to 28.8 m, and smoke detectors mean that a distance of 48 m is permissible. When sprinklers are installed, the permissible distance is 48 m, increasing to 72 m when smoke detection is also provided.

Given the open plan nature it is also assumed that there are multiple escape routes within the office, leading to a single final exit. It is therefore at this exit only that a fire may obstruct egress.

The following tables give the successful egress rates for the conditions permitted by the Acceptable Solutions, for the various item and standard fires previously noted.

The success rates provided in Table 5.1 for the office *occupancy*, and are determined from the following scenarios:

- Firstly, on “average” manual detection (as defined in section 3.3.3), where the travel distance is no greater than 24 m, and the fire may be within 1 m, 2 m, 3 m, or further than 3 m from the escape route.

- Next, the first row for each fire under the heat detection heading gives the success rate when occupants with a travel distance of no further than 28.8 m respond to heat detection activation. These detectors are assumed to be installed at the maximum compliant spacing (ie scenario 5). The second row gives the success rate for the same conditions, but when the occupants respond to “average” manual detection rather than waiting for heat detector activation.

- A similar arrangement is given for scenarios where smoke detection is provided, and the travel distance is no more than 48 m. Again, scenario 5 smoke detection response is given in the first row, with average manual detection response in the second row.

- Finally, sprinkler protection is considered. The first column in this section assumes a travel distance no greater than 48 m, response to manual detection, and that the fire is controlled by sprinklers installed to compliant spacings (ie scenario 5). In the second column, the success rate for response to smoke detection is given and a travel distance of 72 m, with the second row number being response to manual detection at the same travel distance. The effect of the separation of the fire from the escape route has not been specifically addressed in this table, as the effect of sprinkler operation on the fire size is assumed to result in a fairly uniform fire size as noted in section 4.1.2.

- Where the proximity of the fire to the egress route has reduced the egress success rate, the cell is highlighted.

The equivalent results for the corresponding travel distance limits are also given for the two crowd *occupancies* in Table 5.2 and Table 5.3.

These results confirm the following trends previously noted:

- As the travel distance (and hence the firecell size) increases, so does the probability of a successful evacuation, even when the means of detection remains manual.

- At the longer travel distances, usually only permitted when smoke detectors are installed, there is no “rule” apparent that indicates that smoke detection will occur before manual detection, or vice versa. This appears to depend on the fire and firecell.

    - A smouldering fire is most likely to activate smoke detectors before an adequate smoke layer has formed to allow manual detection, but

    - if the plateau of heat release rate is a little higher, then manual detection may occur first in smaller firecells.

    - If the fire has a slow growth rate, manual detection will occur first, but medium and faster fire growth rates reverses the order.

- Many of the fires analysed have a very small number of successful outcomes. However, relatively few of the failures are controlled by the separation between the fire and the escape route. When the travel distance is less than 24 m, none of the outcomes fail due to radiation only. As the travel distance increases to 28.8 m, some fires may obstruct up to 14% of the outcomes, and when the travel distance is 48 m, this increases to up to 81% (in the case of the Y5.4/21 Sofa fire in the office scenario).

- Where sprinklers are provided, without smoke detectors, and the travel distance is no more than 48 m, there is little difference in the success rate. When the travel distance is further increased as permitted due to provision of smoke detectors, there is a further increase in the success rates. Much of this increase is due to the increased firecell size and resulting increased tenability time, and not due to improved detection. This can be seen in the increased success rate for manual detection only at the larger distance. Smoke detectors do increase the success rate in large firecells as the volume of smoke required for detection of the fire is much greater than that produced before smoke detectors activate.

To assess the comparative risk of being obstructed by a fire, we look at the probability that the fire might be located where it could obstruct the egress route. The Y5.4/21 Sofa fire has been selected as this is the one that appears to have the greatest obstructive influence on the escape route. The probability of success when the fire is far from the escape route is 0.83, or 83%, reducing to 0.02 or 2% when the fire is 1 m from the escape route. It is assumed that this fire has an equal chance of being located anywhere in the firecell, and that the probabilities of success are as given in Table 5.1 below. Obstruction may occur when the fire is within 3 m of the egress route, but there is a greater risk of obstruction at closer distances. The probability that the fire is within a separation distance, S of the escape route is given in Equation 5.1. Review of the firecell sizes complying with the 48 m travel distance limit indicates an average area of 280 m^2.

$$P_S = \frac{(2 \cdot S + W) \cdot S}{A_{firecell}}$$ **Equation 5.1**

$$P_{S=1m} = \frac{(2 \cdot 1 + 1) \cdot 1}{280} = 0.011$$ **Equation 5.2**

$$P_{S=1-2m} = \frac{[(2 \cdot 2 + 1) \cdot 2] - [(2 \cdot 1 + 1) \cdot 1]}{280} = 0.025$$ **Equation 5.3**

$$P_{S=2-3m} = \frac{[(2 \cdot 3 + 1) \cdot 3] - [(2 \cdot 2 + 1) \cdot 2]}{280} = 0.039$$ **Equation 5.4**

$$P_{S=>3m} = \frac{280 - [(2 \cdot 3 + 1) \cdot 3]}{280} = 0.925$$ **Equation 5.5**

To consider the probability that the fire is in that location, combined with the probability that it will prevent egress. For a 1 m separation, the probability of failure due to radiation is the probability of failure due to tenability, 0.83, minus the probability of failure where the fire is 1 m from the escape route, 0.02, giving a difference of 0.81. There is a 0.02 probability of success where the separation is 1 m, and a 0.83 probability of success when the fire is not close to the escape route (refer Table 5.1 for the source of the probabilities). Similarly for 2 m and 3 m, the resulting probabilities are 0.55(=0.83-0.28) and 0.03(=0.83-0.80) respectively, and the probability of failure due to loss of tenability is 0.17 (being the converse of the probability of success which is 0.83). The probability, then, of failure is calculated in Equation 5.6, at 0.18. Conversely, the probability of success is 0.82 - just 0.01 less than the probability of failure if the fire is distant from the escape route.

$$P_{failure} = 0.011 \times 0.81 + 0.025 \times 0.55 + 0.039 \times 0.03 + 0.925 \times 0.17 = 0.18$$ **Equation 5.6**

To summarise, the probability of successful egress for a firecell is related to the size of the firecell, and the larger the firecell, the more likely a successful result will occur.

There are a number of item fires that have a particularly poor success rate. In particular, the wardrobe fire, the sofa fire from NIST, and other soft furniture to a slightly lesser extent. While the wardrobe may be a particularly severe test, the other furniture items are not particularly unusual in these situations and therefore be an unexpected hazard

To the advantage of the occupants in this situation, there is, however, a tendency for real fires to smoulder initially, or even to burn at a slower initial heat release rated before properly catching. This stage has a significant advantage in that the smoke produced will tend to hasten manual detection, and if installed, smoke detection, increasing the time otherwise available for evacuation. This phase does not appear to significantly reduce the available egress time, unless detection is dependent on heat detector activation, which is less likely to occur at a similarly early stage.

As the firecell size and the travel distance increase, the probability that the fire will be located in the area that may obstruct egress decreases. Note that the above comment assumes that the open plan nature of the ceiling reflects the provision of multiple routes to the final exit. If there is a single route, then the area in which the fire might cause obstruction is greater, and the probability of obstruction is correspondingly higher.

Fire	Manual Detection (24 m travel distance)				Heat Detection (28.8 m travel distance)				Smoke Detection (48 m travel distance)				Sprinklers (48 m travel distance)	Sprinklers & Smoke Detectors (72 m travel distance)
	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m		
Office Y0/21	22%	22%	22%	22%	0%[*] 46%[‡]	0% 46%	0% 46%	0% 46%	84%[†] 71%[‡]	84% 71%	84% 71%	84% 71%	71%[§]	92%[†] 85%[‡]
Office Y0/22	35%	35%	35%	35%	0%[*] 40%[‡]	0% 40%	0% 40%	0% 40%	60%[†] 63%[‡]	60% 63%	60% 63%	60% 63%	63%[§]	79%[†] 76%[‡]
2 Panel Workstation	14%	14%	14%	14%	0%[*] 23%[‡]	0% 25%	0% 25%	0% 25%	82%[†] 8%[‡]	85% 21%	85% 47%	85% 47%	47%[§]	92%[†] 68%[‡]
3 Panel Workstation	0%	0%	0%	0%	16%[*] 18%[‡]	18% 18%	18% 18%	18% 18%	82%[†] 23%[‡]	82% 32%	82% 60%	82% 60%	60%[§]	92%[†] 76%[‡]
Wardrobe Y3.1/13	0%	0%	0%	0%	0%[*] 0%[‡]	0% 0%	0% 0%	0% 0%	0%[†] 0%[‡]	0% 0%	0% 0%	2% 0%	0%[§]	4%[†] 0%[‡]
Small Dresser	17%	17%	17%	17%	3%[*] 31%[‡]	3% 31%	3% 31%	3% 31%	86%[†] 34%[‡]	86% 54%	86% 54%	86% 54%	54%[§]	94%[†] 67%[‡]

Fire | Manual Detection (24 m travel distance) | Heat Detection (28.8 m travel distance) | Smoke Detection (48 m travel distance) | Sprinklers (48 m | Sprinklers & Smoke

[*] These percentage success rates assume response to heat detector activation
[†] These percentage success rates assume response to smoke detector activation
[§] These percentage success rates assume response to manual detection, with sprinkler activation usually occurring later
[‡] These percentage success rates assume response to manual detection

Fire	Manual Detection (24 m travel distance)				Heat Detection (28.8 m travel distance)				Smoke Detection (48 m travel distance)				Sprinklers (48 m travel distance)	Sprinklers & Smoke Detectors (72 m travel distance)
	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m		
Bookcase Y3.3/13	18%	18%	18%	18%	0%[*]	0%	0%	0%	10%[†]	47%	52%	52%	52%[§]	74%[†]
					25%[‡]	37%	37%	37%	9%[‡]	39%	52%	52%		60%[‡]
Stackable Chairs Y5.0/14	0%	13%	13%	13%	0%[*]	0%	0%	0%	1%[†]	42%	53%	53%	31%[§]	76%[†]
					0%[‡]	14%	14%	14%	0%[‡]	8%	25%	25%		50%[‡]
Easy Chair Y5.3/10	3%	11%	11%	11%	0%[*]	0%	0%	0%	0%[†]	0%	31%	13%	8%[§]	61%[†]
					2%[‡]	7%	12%	12%	0%[‡]	2%	10%	10%		24%[‡]
Sofa Y5.4/21	0%	6%	9%	9%	0%[*]	0%	0%	0%	2%[†]	28%	80%	83%	12%[§]	91%[†]
					0%[‡]	3%	8%	10%	0%[‡]	1%	4%	10%		25%[‡]
Loveseat	6%	6%	6%	6%	0%[*]	0%	0%	0%	0[†]%[†]	41%	41%	41%	29%[§]	68%[†]
					8%[‡]	10%	10%	10%	3%[‡]	23%	29%	29%		50%[‡]
Sofa	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	31%	34%	34%	18%[§]	66%[†]
					0%[‡]	2%	2%	2%	0%[‡]	7%	16%	16%		45%[‡]

[*] These percentage success results assume response to heat detector activation
[†] These percentage success results assume response to smoke detector activation
[§] These percentage success rates assume response to manual detection, with sprinkler activation usually occurring later
[‡] These percentage success results assume response to manual detection

	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m	travel distance)	Detectors (72 m travel distance)
Slow Fire	35%	35%	35%	35%	0%[*] 54%[‡]	0% 54%	0% 54%	0% 54%	42%[†] 71%[‡]	42% 71%	42% 71%	42% 71%	71%[§]	69%[†] 82%[‡]
Medium Fire	12%	12%	12%	12%	0%[*] 23%[‡]	0% 23%	0% 23%	0% 23%	13%[†] 9%[‡]	57% 45%	57% 45%	57% 45%	46%[§]	78%[†] 62%[‡]
Fast Fire	0%	0%	0%	0%	0%[*] 0%[‡]	0% 0%	0% 0%	0% 0%	0%[†] 0%[‡]	0% 0%	7% 0%	7% 0%	0%[§]	35%[†] 6%[‡]
Ultra-Fast Fire	0%	0%	0%	0%	0%[*] 0%[‡]	0% 0%	0% 0%	0% 0%	0%[†] 0%[‡]	0% 0%	1% 0%	10% 0%	0%[§]	12%[†] 0%[‡]

Table 5.1 : Probability of Successful Evacuation from Work Occupancy

[*] These percentage success results assume response to heat detector activation
[†] These percentage success results assume response to smoke detector activation
[§] These percentage success results assume response to manual detection, with sprinkler activation usually occurring later
[‡] These percentage success results assume response to manual detection

Fire	Manual Detection (18 m travel distance)				Heat Detection (21.6 m travel distance)				Smoke Detection (36 m travel distance)				Sprinklers (36 m travel distance)	Sprinklers & Smoke Detectors (54 m travel distance)
	1 m	2 m	3 m	>3m	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m		
Office Y0/21	0%	0%	0%	0%	0%[*]	0%	0%	0%	50%[†]	50%	50%	50%	57%[§]	84%[†]
					5%[‡]	5%	5%	5%	46%[‡]	46%	46%	46%		75%[‡]
Office Y0/22	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	21%	21%	21%	22%[§]	57%[†]
					12%[‡]	12%	12%	12%	3%[‡]	22%	22%	22%		48%[‡]
2 Panel Workstation	0%	0%	0%	0%	0%[*]	0%	0%	0%	1%[†]	33%	43%	43%	13%[§]	70%[†]
					0%[‡]	0%	0%	0%	0%[‡]	4%	13%	13%		34%[‡]
3 Panel Workstation	0%	0%	0%	0%	0%[*]	0%	0%	0%	35%[†]	50%	50%	50%	25%[§]	76%[†]
					0%[‡]	0%	0%	0%	1%[‡]	19%	25%	25%		48%[‡]
Wardrobe Y3.1/13	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	0%	0%	0%	0%[§]	0%[†]
					0%[‡]	0%	0%	0%	0%[‡]	0%	0%	0%		0%[‡]
Small Dresser	0%	0%	0%	0%	4%[*]	4%	4%	4%	46%[†]	56%	56%	56%	14%[§]	79%[†]
					4%[‡]	4%	4%	4%	2%[‡]	14%	14%	14%		30%[‡]

[*] Response to heat detector activation
[†] Response to smoke detection
[§] Response to manual detection
[‡] Response to manual detection

Fire	Manual Detection (18 m travel distance)				Heat Detection (21.6 m travel distance)				Smoke Detection (36 m travel distance)				Sprinklers (36 m travel distance)	Sprinklers & Smoke Detectors (54 m travel distance)
	1 m	2 m	3 m	>3m	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m		
Bookcase Y3.3/13	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	2%	4%	4%	11%§	36%†
					0%‡	0%	0%	0%	0%‡	5%	11%	11%		17%‡
Stackable Chairs Y5.0/14	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	5%	8%	9%	1%§	41%†
					0%‡	0%	0%	0%	0%‡	0%	1%	1%		12%‡
Easy Chair Y5.3/10	0%	6%	6%	6%	0%*	0%	0%	0%	0%†	0%	31%	31%	1%§	16%†
					0%‡	3%	3%	3%	0%‡	1%	1%	1%		2%‡
Sofa Y5.4/21	0%	0%	0%	0%	0%*	0%	0%	0%	1%†	10%	29%	29%	1%§	59%†
					0%‡	0%	0%	0%	0%‡	1%	1%	1%		2%‡
Loveseat	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	3%	3%	3%	2%§	26%†
					0%‡	0%	0%	0%	0%‡	1%	2%	2%		14%‡
Sofa	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	0%	0%	0%	0%§	23%†
					0%‡	0%	0%	0%	0%‡	0%	0%	0%		9%‡

* Response to heat detector activation
† Response to smoke detector activation
§ Response to sprinkler activation
‡ Response to manual detection

Fire	Manual Detection (18 m travel distance)				Heat Detection (21.6 m travel distance)				Smoke Detection (36 m travel distance)				Sprinklers (36 m travel distance)	Sprinklers & Smoke Detectors (54 m travel distance)
	1 m	2 m	3 m	>3m	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m		
Slow Fire	8%	8%	8%	8%	0%*	0%	0%	0%	0%†	3%	3%	3%	44%§	38%†
					13%‡	13%	13%	13%	41%‡	44%	44%	44%		58%‡
Medium Fire	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	4%	4%	4%	9%§	41%†
					0%‡	0%	0%	0%	0%‡	9%	9%	9%		27%‡
Fast Fire	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	0%	7%	7%	0%§	35%†
					0%‡	0%	0%	0%	0%‡	0%	0%	0%		6%‡
Ultra-Fast Fire	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	0%	0%	0%	0%§	12%†
					0%‡	0%	0%	0%	0%‡	0%	0%	0%		0%‡

Table 5.2 : Probability of Successful Evacuation from Mobile Crowd (Retail) Occupancy

* Response to heat detector activation
† Response to smoke detector activation
§ Response to manual detection
‡ Response to manual detection

Fire	Manual Detection (18 m travel distance)				Heat Detection (21.6 m travel distance)				Smoke Detection (36 m travel distance)				Sprinklers (36 m travel distance)	Sprinklers & Smoke Detectors (54 m travel distance)
	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m		
Office Y0/21	0%	0%	0%	0%	0%*	0%	0%	0%	42%†	42%	42%	42%	44%§	81%†
					0%‡	0%	0%	0%	30%‡	30%	30%	30%		68%‡
Office Y0/22	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	0%	0%	4%	8%§	43%†
					0%‡	0%	0%	6%	0%‡	0%	0%	8%		34%‡
2 Panel Workstation	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	32%	32%	32%	8%§	59%†
					0%‡	0%	0%	0%	0%‡	8%	8%	8%		26%‡
3 Panel Workstation	0%	0%	43%	43%	0%*	12%	84%	84%	3%†	40%	85%	85%	55%§	83%†
					0%‡	0%	44%	44%	0%‡	1%	44%	44%		55%‡
Wardrobe Y3.1/13	0%	0%	0%	0%	0%*	0%	0%	0%	0%†	0%	0%	0%	0%§	0%†
					0%‡	0%	0%	0%	0%‡	0%	0%	0%		0%‡
Small Dresser	0%	0%	0%	0%	0%*	0%	0%	0%	16%†	33%	33%	33%	5%§	66%†
					0%‡	0%	0%	0%	0%‡	5%	5%	5%		20%‡

* Response to heat detector activation
† Response to smoke detector activation
§ Response to manual detection
‡ Response to manual detection

Fire	Manual Detection (18 m travel distance)				Heat Detection (21.6 m travel distance)				Smoke Detection (36 m travel distance)				Sprinklers (36 m travel distance)	Sprinklers & Smoke Detectors (54 m travel distance)
	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m		
Bookcase Y3.3/13	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	1%	2%	2%	3%[§]	24%[†]
					0%[‡]	0%	0%	0%	0%[‡]	2%	3%	3%		7%[‡]
Stackable Chairs Y5.0/14	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	1%	2%	4%	0%[§]	29%[†]
					0%[‡]	0%	0%	0%	0%[‡]	0%	0%	0%		6%[‡]
Easy Chair Y5.3/10	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	0%	0%	0%	0%[§]	9%[†]
					0%[‡]	0%	0%	0%	0%[‡]	0%	0%	0%		0%[‡]
Sofa Y5.4/21	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	0%	0%	0%	0%[§]	39%[†]
					0%[‡]	0%	0%	0%	0%[‡]	0%	0%	0%		0%[‡]
Loveseat	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	1%	2%	2%	1%[§]	19%[†]
					0%[‡]	0%	0%	0%	0%[‡]	1%	1%	1%		7%[‡]
Sofa	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	0%	0%	0%	0%[§]	14%[†]
					0%[‡]	0%	0%	0%	0%[‡]	0%	0%	0%		5%[‡]

[*] Response to heat detector activation
[†] Response to smoke detector activation
[§] Response to manual detection
[‡] Response to manual detection

Fire	Manual Detection (18 m travel distance)				Heat Detection (21.6 m travel distance)				Smoke Detection (36 m travel distance)				Sprinklers (36 m travel distance)	Sprinklers & Smoke Detectors (54 m travel distance)
	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m	1 m	2 m	3 m	>3 m		
Slow Fire	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	0%	0%	0%	31%[§]	30%[†]
					0%[‡]	0%	0%	0%	24%[‡]	31%	31%	31%		48%[‡]
Medium Fire	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	0%	0%	0%	0%[§]	29%[†]
					0%[‡]	0%	0%	0%	0%[‡]	0%	0%	0%		14%[‡]
Fast Fire	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	0%	2%	2%	0%[§]	24%[†]
					0%[‡]	0%	0%	0%	0%[‡]	0%	0%	0%		3%[‡]
Ultra-Fast Fire	0%	0%	0%	0%	0%[*]	0%	0%	0%	0%[†]	0%	0%	0%	0%[§]	7%[†]
					0%[‡]	0%	0%	0%	0%[‡]	0%	0%	0%		0%[‡]

Table 5.3 : Probability of Successful Evacuation from Crowd (Bar) Occupancy

[*] Response to heat detector activation
[†] Response to smoke detector activation
[§] Response to manual detection
[‡] Response to manual detection

6 ANALYSIS OF FIRE SERVICE STATISTICS

6.1 Injury Occurrence and Severity

The following section is based on information provided by the New Zealand Fire Service, detailing the numbers and circumstances of injuries received as a result of fires during the 2000/01 reporting period and the 2001/02 reporting period. The main data is reported in Table 6.1.

Out of all fires, approximately 2% result in injuries. When the fire involves a structure (ie a Structure Fire), the injury rate increases to approximately 5%. The greatest number and percentage of injuries occur in residential fires, with the least occurring in active purpose group fires (both crowd and working *occupancies* have low numbers and rates of injuries). Structure fires are typically classified as either “with damage” or “without damage”, the latter being where there is no damage to the building fabric.

Of greatest relevance to this study are the numbers and seriousness of injuries sustained by people who were alert at the time of the fire, as well as the situation in which they were received. Some of the residential fires may be included if the occupants were not asleep or otherwise incapacitated.

In Table 6.2, the initial locations, and actions of these occupants is summarised, showing the numbers of occupants in the same area as the fire, whether they were alert, and whether they were injured while escaping, of whether other non-evasive actions were being taken while the injury was sustained.

This information is also presented in graphical form in Figure 6.1 through Figure 6.7

Reference to Figure 6.1 indicates that nearly half the fires that occur in structure do not cause “damage” (ie damage to the building fabric).

Figure 6.2 shows what proportion of structure fires involve the different purpose groups. The most significant group is residential fires, comprising nearly 70% of all fires involving structures. There are relatively few “Working Environment” or “Crowd Use” structure fires, each comprising approximately 10% of structure fires.

Figure 6.3 indicates where victims were when injured, and whether they were awake. Given the large proportion of residential fires, it is not surprising that 44% were asleep.

A total of 36% were awake and in the same space as the fire, with the remainder being elsewhere.

The Building Code is not required to address property protection, and the generally accepted advice is that on discovery of a fire, occupants should notify others then leave the building. It is not generally recommended for occupants to undertake fire-fighting activities due to the risks associated with inadequate tools and protection. Therefore, Figure 6.4 has been created to illustrate the differing rates of injury relating to avoidance behaviour, relative to fire-fighting behaviour. This shows that there is a far greater rate of injury involved in fire-fighting behaviour, with a greater number of more serious injuries.

Figure 6.5 confirms the trends for injury seriousness noted above, although interestingly, the relative proportions of these numbers appear to indicate that fire-fighting activities tend to result in less serious injuries. This is because of the large number of minor injuries sustained during this activity. It would be reasonable to assume that these injuries would not have occurred if the victim had avoided the fire instead. The greatest risk of severe injury occurs to occupants who are asleep or otherwise incapacitated. The relative occurrence of fire-fighting behaviour versus avoidance is not known, so the risk of injury for each type of behaviour cannot be quantified.

Figure 6.6 indicates the number of fires in each category that result in injuries to occupants. Mostly, structure fires are involved, but there is relatively little difference whether the fire is one involving damage to the structure or not. Most of the structure fires are in residential properties, with comparatively few being in “crowd” or “working” environments.

The general conclusion that can be drawn from this is that residential fires are most likely to result in injuries to the occupants. With this *occupancy*, there is a reasonable chance that occupants may be asleep or incapacitated, and also it is expected (though this cannot be confirmed by the data) that those who are awake will tend to attempt to fight the fire.

Type of Fire	2000/01		2001/02		Total 2000-2002	
All Fires	22280		20424		42704	
no. of injuries	343	1.5%	477	2.3%	820	1.9%
no. resulting in injuries	300	1.3%	425	2.1%	725	1.7%
All Structure Fires (including unclassified)	6418	29%	6554	32%	12972	30%
no. of injuries	250	3.9%	386	5.9%	636	4.9%
no. resulting in injuries	228	3.6%	346	5.3%	574	4.4%
Structure Fire with damage	2388	37%	2625	40%	5013	39%
no. of injuries	135	5.7%	239	9.1%	374	7.5%
no. resulting in injuries	119	5.0%	211	8.0%	330	6.6%
Structure Fire without damage	3117	49%	3101	47%	6218	48%
no. of injuries	114	3.5%	146	4.3%	260	3.9%
no. resulting in injuries	108	3.7%	134	4.7%	242	4.2%
Residential Structure Fires	4239	66%	4788	73%	9027	70%
no. of injuries	232	5.5%	357	7.5%	589	6.5%
no. resulting in injuries	211	5.0%	317	6.6%	528	5.8%
Working Environment Structure Fires	667	10%	831	13%	1498	12%
no. of injuries	12	1.8%	12	1.4%	24	1.6%
no. resulting in injuries	11	1.6%	12	1.4%	23	1.5%
Crowd Use Structure Fires	522	8%	675	10%	1197	9%
no. of injuries	6	1.1%	17	2.5%	23	1.9%
no. resulting in injuries	6	1.1%	17	2.5%	23	1.9%
All Active Purpose Group Structure Fires	1189	19%	1506	23%	2695	21%
No. of injuries	18	1.5%	29	1.9%	47	1.7%
No. resulting in injuries	17	1.4%	29	1.9%	46	1.7%

Table 6.1 : Fire Service Injury Statistics

Note: Injuries and Fires resulting in injuries are also indicated as a percentage of the total number of fires in the relevant category and period.
The number of structural fires are also indicated as a percentage of the total number of fires.
The number of categories of structural fires (eg structural with damage, crowd use) are also indicated as a percentage of all structural fires.

Injuries and Severity		2000/01		2001/02		Total	
Total Injuries in Structure Fires		250		386		636	
Injury Severity	Fatal	19	8%	29	8%	48	8%
	Life Threatening	18	7%	10	3%	28	4%
	Moderate	90	36%	170	44%	260	41%
	Slight	123	49%	177	46%	300	47%
Injured Occupants Awake		139	56%	215	56%	354	56%
Injury Severity	Fatal	5	4%	2	1%	7	2%
	Life Threatening	6	4%	2	1%	8	2%
	Moderate	43	31%	103	48%	146	41%
	Slight	84	60%	108	50%	192	54%
Injured Occupants Asleep or otherwise incapacitated		111	44%	171	44%	282	44%
Injury Severity	Fatal	14	13%	27	16%	41	15%
	Life Threatening	12	11%	8	5%	20	7%
	Moderate	47	42%	67	39%	114	40%
	Slight	38	34%	68	40%	106	38%
Injured Occupants awake and in the same space as the fire		85	34%	130	34%	215	34%
Injury Severity	Fatal	3	4%	2	2%	5	2%
	Life Threatening	4	5%	1	1%	5	2%
	Moderate	22	26%	59	45%	81	38%
	Slight	56	66%	68	52%	124	58%
Injured Occupants awake but not in same space as fire		54	22%	85	22%	139	22%
Injury Severity	Fatal	2	2%	2	2%	5	2%
	Life Threatening	2	2%	1	1%	5	2%
	Moderate	21	25%	59	45%	81	38%
	Slight	29	34%	68	52%	124	58%
Occupants Escape		26	31%	48	37%	74	34%
Injury Severity	Fatal	1	4%	2	4%	3	4%
	Life Threatening	1	4%	0	0%	1	1%
	Moderate	9	35%	25	52%	34	46%
	Slight	15	58%	21	44%	36	49%

Occupants Escape	Do Not attempt	59	69%	82	63%	141	66%
Injury Severity	Fatal	2	3%	0	0%	2	1%
	Life Threatening	3	5%	1	1%	4	3%
	Moderate	13	22%	34	41%	47	33%
	Slight	41	69%	47	57%	88	62%

Table 6.2 : Injury Severity, Occupant Location, Alertness and Response

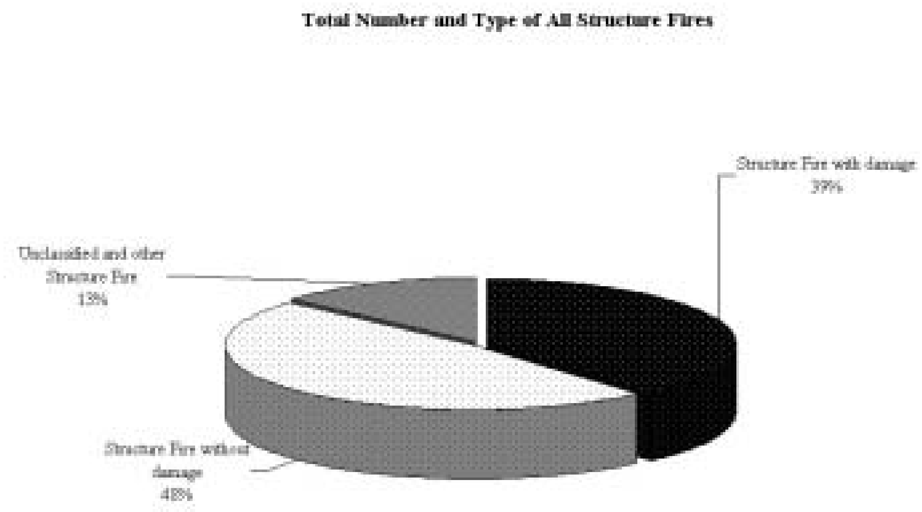

Figure 6.1 : Classification of Structure Fires

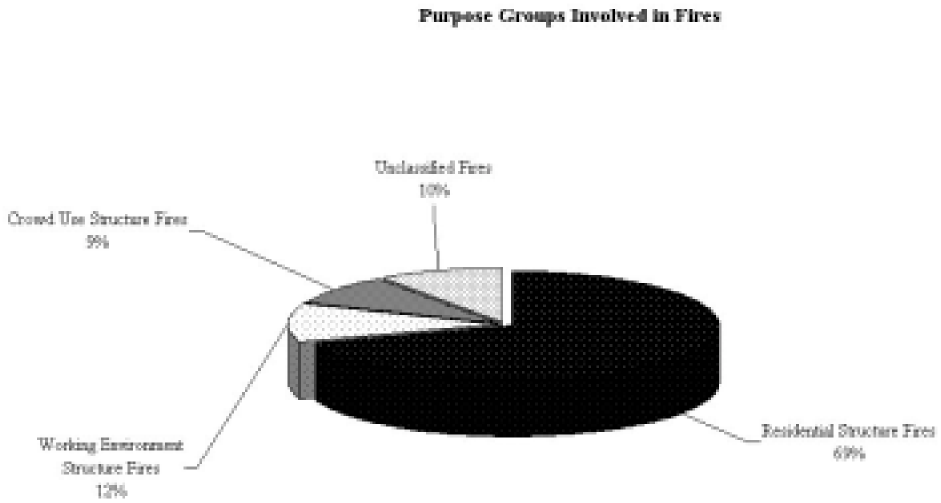

Figure 6.2 : Purpose Groups in Structure Fires

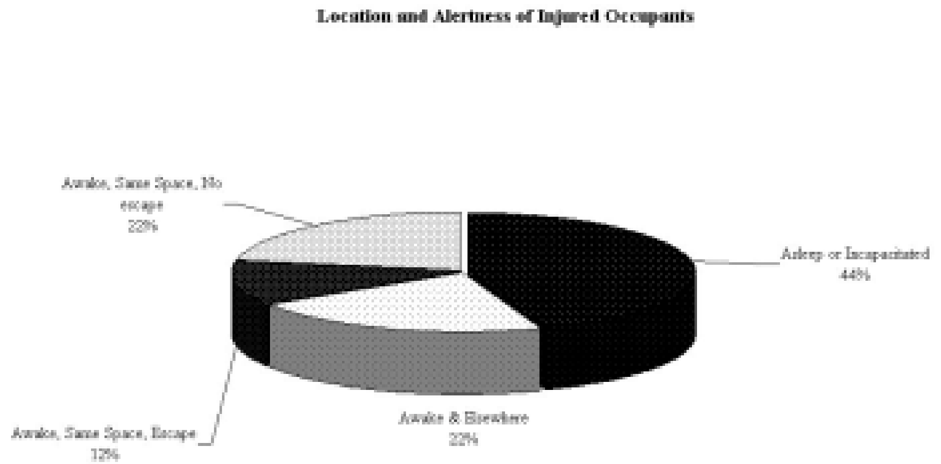

Figure 6.3 : Location and Alertness of Injured Occupants

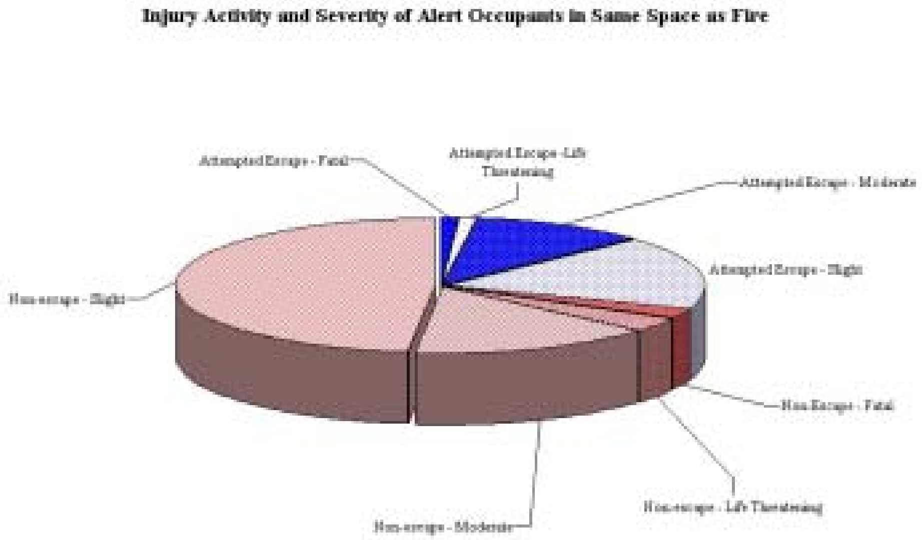

Figure 6.4 : Activity of Injured Occupants

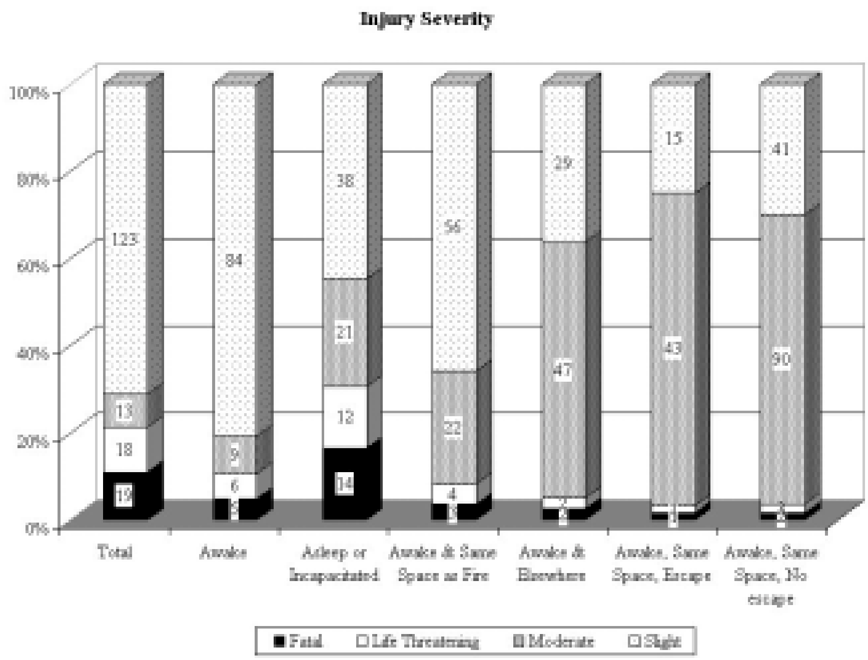

Figure 6.5 : Injury Severity

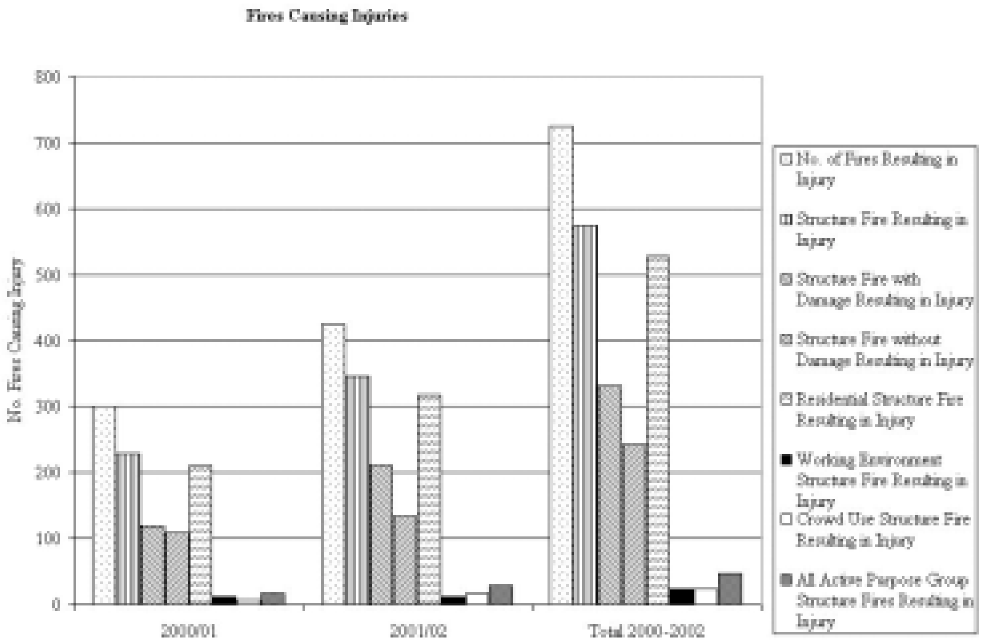

Figure 6.6 : Fires Causing Injuries

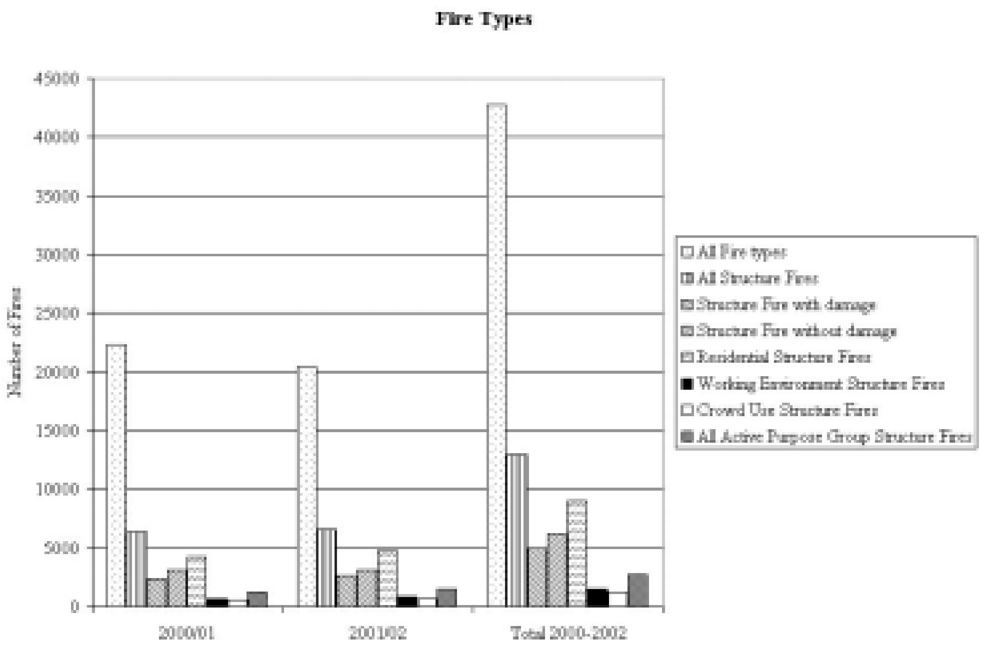

Figure 6.7 : Fire Types

6.2 Risk of Injury

While the above statistics cannot be used to directly confirm the accuracy of all aspects of the model, they can be used to give an indication of the relative level of risk of injury during a fire.

Considering first the workplace situations, fewer than 2% of the fires resulted in injuries. These injuries were either moderate or slight – none were fatal or life threatening.

Next, consider crowd situations (including retail). There is a similar level of injury rate to that for work-places, being approximately 2%. Again, there were no fatalities, and only a single life threatening injury (the victim was involved in an irrational action).

The above record indicates a very low risk of injury, unlike that predicted by the models for small firecells (which are assumed to be more common than larger ones). This would therefore seem to confirm previous comments that in such situations, occupants will tend to modify their behaviour as conditions in the firecell change, to suit the conditions.

7 CONCLUSIONS

7.1 Egress Time

In small firecells particularly, the time required for egress may be dominated by the time required for people to pass through the minimum permissible door width. Where the maximum travel distance is 24 m, queuing will tend to occur when there are more than 15-20 people in the firecell, so when the permitted 50 are present, queuing, rather than travel time, governs the time required for egress. Therefore, if the doors provided are sufficiently wide so as not to delay the egress of the number of people in the firecell, then the number of occupants need have no effect on the egress time, and there is no fire safety reason to limit the number of people to 50.

7.2 Available Time for Egress

7.2.1 Tenability

The main aspect of the fire that tends to prevent successful egress is the loss of tenability due to descent of the smoke layer.

The time available for egress is shown to be dependent on the firecell size, with smaller firecells having the shortest available time. In most of the fire and occupancy scenarios considered, this time tended to be inadequate whatever the means of detection and/or suppression was provided. This is typically because detection is often predicted after tenability of the firecell is lost.

7.2.2 Obstruction due to Radiation

Where a firecell has multiple circulation paths leading to a single exit point, the risk that this final exit will be obstructed is very small. It is here that the benefits of restricting the length of the “common path of travel” (the length of path through which people must pass) by the UBC 1997 becomes apparent. It is this length which most affects the probability of obstruction. In this study, the length is effectively 2 –3 m, but no restrictions other than the total dead end path length are made by other documents reviewed. If this is restricted to a small length, then the critical area in which the fire may obstruct the route is also restricted, thus reducing the probability that the route may be obstructed.

The required separation between the fire and the escape route to permit egress is dependent to some extent on the fire growth rate and the travel distance. It is generally possible to egress as close as 1 m to a fire with a slow growth rate, but when it has a fast growth rate, a separation of 2-3 m is required. The 3 m separation is typically only required where the travel distance exceeds 50 m – a situation not permitted by the Acceptable Solutions.

The effective risk of obstruction is demonstrated by considering a sofa fire in a firecell with maximum travel distance of 48 m (ie a work environment with smoke detection). In this case, the risk of obstruction is approximately 1%. Where the fire was assumed not to obstruct, and egress was dependent on tenability only, the success rate was 83%, and when the risk of obstruction was included, it reduced only to 82%. This example was selected as it appeared to show the greatest risk of obstruction, and serves to demonstrate the slightness of the risk.

7.3 Means of Detection and Suppression

Where the occupants are in the same open space as the fire, and the firecell size is not too great (with a maximum travel distance no greater than 30 m) manual detection may occur first, followed by smoke detector activation, and finally heat detectors and sprinklers. In larger firecells, smoke detection may occur before manual detection. The warning provided by heat detection is typically too late to allow many successful egress scenarios. Even when sprinklers are provided, manual detection or smoke detector activation are required to provide adequate warning.

While most attention has been directed at detection solutions compliant with the Fire Alarm Standard, NZS 4512:1997, it can be shown that the installation of detectors at closer spacings can have a significant effect on the detection time, in some cases reducing it by 1 minute or more. A similar effect is noted on the rates of successful evacuation.

The installation of sprinklers does result in some improvement of success rates, and this is mainly due to the effect of controlling the radiation from the fire and its potential to obstruct the escape route. While the sprinkler does tend to control the fire size, smoke production continues, and loss of tenability of the firecell is generally delayed only in the larger firecells. In smaller firecells, the effect is less noticeable.

7.4 Risks Associated with Scenarios Compliant with the Acceptable Solutions C/AS1

Where the maximum permissible travel distances are short, the tenability time is typically short as well, and consequently few successful outcomes are predicted. However, a review of the Fire Service Statistics indicates that the risk of injury in a fire in a working environment is low, at 1.6%, and hence it is likely that the manual detection and pre-movement times predicted in this study are too great.

In larger firecells, the success rate improves, primarily due to the greater tenability time, even when only manual detection by the occupants is available. Although the fire size when evacuation is completed from such fire cells may be larger, with radiation obstructing a greater area, the greater area of the firecell means that the risk of the fire being within such a critical area is low, and there is little reduction in the success rate due to that risk.

The provision of sprinklers reduces the risk of radiation from a fire preventing egress, but only improves the tenability time of larger firecells. While there are clearly benefits in the reduced risk of obstruction of the escape route by the fire, the benefits attributed to the provision of a sprinkler system (permitting increased travel distances) are not reflected in the results of this study.

The 50 person limit noted earlier in section 7.1 appears to be unnecessary, provided the door width is adequate to ensure unimpeded egress.

7.5 Cautions and Limitations of these Findings

This report has focused primarily on open plan firecells, with no subdivision of the ceiling area by partitions. Where space is partitioned in this way, smoke spread to other areas is restricted, resulting in delays to manual detection as well as delay to the loss of tenability of other spaces. However, loss of tenability in the space of fire start will occur much sooner due to the compartment size, and the reduced smoke storage area. If this space were part of the single escape route from the firecell, then this situation would pose a significant hazard to occupants forced to evacuate via the space. In such situations, automatic detection is the most effective and certain means of detection. While this situation is not directly addressed in the Acceptable Solutions to the New Zealand Building Code, the Approved Documents for England and Wales require smoke detection to be provided in this intervening room.

While the provision of a sprinkler system has been shown to have little effect on life safety, this should not detract from the increased property protection provided by such early control and possible suppression of a fire.

Finally, the review of the number of occupants permitted to be served by a single escape route has been undertaken purely on a fire safety basis, assuming an accidental fire. It is possible that there are other reasons for maintaining the limit of 50 people that relate to acceptable risk in case of malicious attack on the single exit. It may be considered "acceptable" for 50 people, but not 51 people, to be trapped by an arsonist or similar non-accidental scenario. It is noted, however, that it would not be impossible for an arsonist with an accomplice to have a similar effect on two escape routes.

7.6 Further Work

7.6.1 Review of the Acceptable Solutions C/AS1

This study, and the associated spreadsheets developed in the process, could be used to assist in a review of the travel distances and detector benefits in the Acceptable

Solutions, to result in more appropriate and equivalent risk levels for open plan, open path travel.

7.6.2 Assessment of Other Detection Methods

It may also be appropriate, with the development of detectors activated by different fire cues, eg carbon monoxide detectors, to expand the spreadsheet to assess the response of these under standard and item fires. The probability of successful evacuation for the different scenarios, and possible comparison with other automatic detection methods already considered could also be used. Such a study could be carried out in conjunction with a review of the Acceptable Solutions if these detectors were considered appropriate to include in that document.

7.6.3 Manual Detection and Pre-Movement Times in Small Firecells

As noted earlier, those assumed in this model appear to be unreasonably long for small firecells where the occupants are in closer proximity to the fire. Modification and development of alternative methods to determine these times would allow a more realistic risk assessment to be completed for smaller firecells, and assist in the preparation of specific designs as alternative solutions to the Acceptable Solutions.

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APPENDICES

9 : FIRE RELATED CLAUSES IN THE NEW ZEALAND BUILDING CODE

1992/150 *Building Regulations 1992* 21

FIRST SCHEDULE—*continued*

Clause C1—OUTBREAK OF FIRE

Provisions	Limits on application
OBJECTIVE **C1.1** The objective of this provision is to safeguard people from injury or illness caused by *fire*. **FUNCTIONAL REQUIREMENT** **C1.2** In *buildings* fixed appliances using the controlled combustion of solid, liquid or gaseous fuel, shall be installed in a way which reduces the likelihood of *fire*. **PERFORMANCE** **C1.3.1** Fixed appliances and services shall be installed so as to avoid the accumulation of gases within the installation and in *building* spaces, where heat or ignition could cause uncontrolled combustion or explosion. **C1.3.2** Fixed appliances shall be installed in a manner that does not raise the temperature of any *building element* by heat transfer or concentration to a level that would adversely affect its physical or mechanical properties or function.	

FIRST SCHEDULE—*continued*

Clause C2—MEANS OF ESCAPE

Provisions	Limits on application

OBJECTIVE

C2.1 The objective of this provision is to:

(a) Safeguard people from injury or illness from a *fire* while escaping to a *safe place*, and

(b) Facilitate *fire* rescue operations.

FUNCTIONAL REQUIREMENT

C2.2 *Buildings* shall be provided with *escape routes* which:

(a) Give people *adequate* time to reach a *safe place* without being overcome by the effects of *fire*, and

(b) Give fire service personnel *adequate* time to undertake rescue operations.

PERFORMANCE

C2.3.1 The number of *open paths* available to each person escaping to an *exitway* or *final exit* shall be appropriate to:

(a) The *travel distance*.

(b) The number of occupants,

(c) The *fire hazard*, and

(d) The *fire safety systems* installed in the *firecell*.

C2.3.2 The number of *exitways* or *final exits* available to each person shall be appropriate to:

(a) The *open path travel distance*,

(b) The *building height*,

(c) The number of occupants,

(d) The *fire hazard*, and

(e) The *fire safety systems* installed in the *building*.

C2.3.3 *Escape routes* shall be:

(a) Of *adequate* size for the number of occupants,

(b) Free of obstruction in the direction of escape,

FIRST SCHEDULE—*continued*

Provisions	Limits on application
(c) Of length appropriate to the mobility of the people using them,	
(d) Resistant to the spread of *fire* as required by Clause C3 "Spread of Fire",	
(e) Easy to find as required by Clause F8 "Signs",	
(f) Provided with *adequate* illumination as required by Clause F6 "Lighting for Emergency", and	
(g) Easy and safe to use as required by Clause D1.3.3 "Access Routes".	

FIRST SCHEDULE—*continued*

Clause C3—SPREAD OF FIRE

Provisions	Limits on application
OBJECTIVE	
C3.1 The objective of this provision is to:	
(a) Safeguard people from injury or illness when evacuating a *building* during *fire*.	
(b) Provide protection to fire service personnel during firefighting operations.	
(c) Protect adjacent *household units* and *other property* from the effects of *fire*.	
(d) Safeguard the environment from adverse effects of *fire*.	
FUNCTIONAL REQUIREMENT	
C3.2 *Buildings* shall be provided with safeguards against *fire* spread so that:	
(a) Occupants have time to escape to a *safe place* without being overcome by the effects of *fire*,	
(b) Firefighters may undertake rescue operations and protect property,	
(c) Adjacent *household units* and *other property* are protected from damage, and	
(d) Significant quantities of *hazardous substances* are not released to the environment during *fire*.	Requirement C3.2 (d) applies only to *buildings* where significant quantities of *hazardous substances* are stored or processed.
PERFORMANCE	
C3.3.1 Interior surface finishes on walls, floors, ceilings and suspended *building elements*, shall resist the spread of *fire* and limit the generation of toxic gases, smoke and heat, to a degree appropriate to:	
(a) The *travel distance*,	
(b) The number of occupants,	
(c) The *fire hazard*, and	
(d) The active *fire safety systems* installed in the *building*.	

FIRST SCHEDULE—*continued*

Provisions	Limits on application
C3.3.2 *Fire separations* shall be provided within *buildings* to avoid the spread of *fire* and smoke to: (a) Other *firecells*, (b) Spaces intended for sleeping, and (c) *Household units* within the same *building* or *adjacent buildings*.	Performance C3.3.2 shall not apply to *Detached Dwellings*, or within *household units* of *Multi-unit Dwellings*.
C3.3.3 *Fire separations* shall: (a) Where openings occur, be provided with *fire resisting closures* to maintain the *integrity* of the *fire separations* for an *adequate* time, and (b) Where penetrations occur, maintain the *fire resistance rating* of the *fire separation*.	
C3.3.4 *Concealed spaces* and cavities within *buildings* shall be sealed and subdivided where necessary to inhibit the unseen spread of *fire* and smoke.	Performance C3.3.4 shall not apply to *Detached Dwellings*.
C3.3.5 *External walls* and roofs shall have resistance to the spread of *fire*, appropriate to the *fire load* within the *building* and to the proximity of other *household units* and *other property*.	
C3.3.6 Automatic fire suppression systems shall be installed where people would otherwise be: (a) Unlikely to reach a safe place in *adequate* time because of the number of storeys in the *building*, (b) Required to remain within the *building* without proceeding directly to a *final exit*, or where the *evacuation time* is excessive, (c) Unlikely to reach a *safe place* due to confinement under institutional care because of mental or physical disability, illness or legal detention, and the *evacuation time* is excessive, or	

FIRST SCHEDULE—*continued*

Provisions	Limits on application
(d) At high risk due to the *fire load* and *fire hazard* within the *building*.	
C3.3.7 Air conditioning and mechanical ventilation systems shall be constructed to avoid circulation of smoke and *fire* between *firecells*.	
C3.3.8 Where an automatic smoke control system is installed, it shall be constructed to: (a) Avoid the spread of *fire* and smoke between *firecells*, and (b) Protect *escape routes* from smoke until the occupants have reached a *safe place*.	
C3.3.9 The *fire safety systems* installed shall facilitate the specific needs of fire service personnel to: (a) Carry out rescue operations, and (b) Control the spread of *fire*.	
C3.3.10 Environmental protection systems shall ensure a low probability of *hazardous substances* being released to: (a) Soils, vegetation or natural waters, (b) The atmosphere, and (c) *Sewers* or public *drains*.	Performance C3.3.10 applies only to *buildings* where significant quantities of *hazardous substances* are stored or processed.

FIRST SCHEDULE—*continued*

Clause C4—STRUCTURAL STABILITY DURING FIRE

Provisions	Limits on application

OBJECTIVE

C4.1 The objective of this provision is to:

(a) Safeguard people from injury due to loss of structural stability during *fire*, and

(b) Protect *household units* and *other property* from damage due to structural instability caused by *fire*.

FUNCTIONAL REQUIREMENT

C4.2 *Buildings* shall be constructed to maintain structural stability during *fire* to:

(a) Allow people *adequate* time to evacuate safely,

(b) Allow fire service personnel *adequate* time to undertake rescue and firefighting operations, and

(c) Avoid collapse and consequential damage to adjacent *household units* or *other property*.

PERFORMANCE

C4.3.1 Structural elements of *buildings* shall have *fire* resistance appropriate to the function of the elements, the *fire load*, the *fire intensity*, the *fire hazard*, the height of the *buildings* and the *fire* control facilities external to and within them.

C4.3.2 Structural elements shall have a *fire* resistance of no less than that of any element to which they provide support within the same *firecell*.

C4.3.3 Collapse of elements having lesser *fire* resistance shall not cause the consequential collapse of elements required to have a higher *fire* resistance.

10 : VERIFICATION OF SPREADSHEET WITH FPETOOL

To verify that the use of the equations detailed in Section 3 is correct, the output of the spreadsheet for a single scenario has been compared with the results of FPETool. This program has been chosen as the comparison due to its wide acceptance within the industry.

The scenario chosen for comparison is a t^2 fire with a medium growth rate, in a 20 m by 20 m room, with a 3 m high ceiling.

The following detector properties are used:

- Heat detector: distance from fire = 1.4 m, Activation temperature 57 ºC, and RTI of 20 $m^{½}s^{-½}$
- Smoke detector: distance from fire = 4.2 m, Activation temperature 33 ºC, and RTI of 0.01 $m^{½}s^{-½}$
- Sprinkler: distance from fire = 2.1 m, Activation temperature 67 ºC, and RTI of 80 $m^{½}s^{-½}$

The FPETool output for this scenario is attached, and the results of this and the spreadsheet are compared in Table.10.1 : Comparison of Spreadsheet with FPETool. The differences are primarily due to the difference in calculation time steps. FPETool uses a 1 second step, while the spreadsheet, due to the time steps at which the data is available tends to use a 20-30 second step. When the 1 second time step is used, the spreadsheet results match the FPETool results fairly closely. The accuracy of the 20 second time step results is generally within 1-2 time steps, and is considered acceptable.

Output Type	Spreadsheet Prediction 20 second time step	Spreadsheet Prediction 1 second time step	FPETool Prediction
Heat Detector Activation	112 s	125 s	124 s
Smoke Detector Activation	87 s	98 s	92 s
Sprinkler Activation	212 s	220 s	220 s
Tenability Time (for smoke layer to drop to 2.0 m above floor level)	290 s	275 s	250 s

Table.10.1 : Comparison of Spreadsheet with FPETool

```
                            10-20-2002
                            FPETOOL V3.2
--------------------Sprinkler/detector response--------------------

Run title: HEAT

Fire to      Detector       Room      Device       RTI
ceiling      axial dist.    temp.     rating
   m            m            C          C        (m/s)^.5
  3.0          1.4           20         57         20.0


Minimum heat release rate necessary to activate the
detector at the location described is   132 kW

Time(Sec)        RHR(kW    )        Jet (C)        Head/det. (C)
     0               0              20              20
    10               1              21              20
    20               5              24              21
    30              11              27              22
    40              19              30              24
    50              29              33              27
    60              42              37              30
    70              57              41              33
    80              75              45              37
    90              95              49              41
   100             117              54              46
   110             142              58              50
   120             168              63              55
    ---- Detector activation at  124 seconds ----
```

```
                    10-20-2002
                   FPETOOL V3.2
---------------------Sprinkler/detector response--------------------

Run title: SMOKE

Fire to      Detector        Room       Device        RTI
ceiling      axial dist.     temp.      rating
   m             m            C           C        (m/s)^.5
  3.0           4.2          20          33           5.0


Minimum heat release rate necessary to activate the
detector at the location described is     82 kW

Time(Sec)        RHR(kW    )         Jet (C)        Head/det. (C)
     0                0             20              20
    10                1             21              20
    20                5             22              21
    30               11             23              22
    40               19             25              23
    50               29             26              25
    60               42             28              27
    70               57             30              29
    80               75             32              31
    90               95             34              33
    ---- Detector activation at   92 seconds ----
```

10-20-2002
FPETOOL V3.2
---------------------Sprinkler/detector response---------------------

Run title: SPRINKLER

Fire to ceiling	Detector axial dist.	Room temp.	Device rating	RTI
m	m	C	C	(m/s)^.5
3.0	2.1	20	67	80.0

Minimum heat release rate necessary to activate the detector at the location described is 284 kW

0	0	20	20
10	1	21	20
20	5	23	20
30	11	25	20
40	19	27	21
50	29	30	22
60	42	33	22
70	57	36	24
80	75	39	25
90	95	42	27
100	117	46	29
110	142	49	31
120	168	53	33
130	198	57	36
140	229	60	39
150	263	64	42
160	300	68	45
170	338	72	48
180	379	76	52
190	422	81	55
200	468	85	59
210	516	89	63

---- Detector activation at 220 seconds ----

10-20-2002
FPETOOL V3.2

--ASETBX--

Run title: Tenability Time

Heat loss fraction = 0.6
Fire height = 0.0 ft 0.0 m
Room height = 9.8 ft 3.0 m
Room area = 4305.6 sq ft 400.0 sq m

TIME sec	TEMP F	TEMP C	LAYER ft	LAYER m	FIRE kW	FIRE BTU/s
0	70	21.3	9.8	3.0	0.1	0.1
10	71	21.7	9.8	3.0	1.2	1.1
20	73	22.6	9.8	3.0	4.7	4.4
30	75	23.7	9.7	3.0	10.5	10.0
40	77	25.0	9.7	2.9	18.7	17.8
50	80	26.4	9.6	2.9	29.3	27.7
60	82	27.9	9.5	2.9	42.1	40.0
70	85	29.5	9.4	2.9	57.3	54.4
80	88	31.3	9.3	2.8	74.9	71.0
90	92	33.1	9.2	2.8	94.8	89.9
100	95	35.1	9.0	2.8	117.0	111.0
110	99	37.2	8.9	2.7	141.6	134.3
120	103	39.4	8.8	2.7	168.5	159.8
130	107	41.7	8.6	2.6	197.7	187.5
140	112	44.2	8.5	2.6	229.3	217.5
150	116	46.8	8.3	2.5	263.3	249.7
160	121	49.6	8.1	2.5	299.5	284.1
170	126	52.5	8.0	2.4	338.1	320.7
180	132	55.5	7.8	2.4	379.1	359.6
190	138	58.7	7.6	2.3	422.4	400.6
200	144	62.1	7.4	2.3	468.0	443.9
210	150	65.7	7.3	2.2	516.0	489.4
220	157	69.4	7.1	2.2	566.3	537.1
230	164	73.4	6.9	2.1	618.9	587.1
240	172	77.6	6.7	2.0	673.9	639.2
250	180	82.0	6.5	2.0	731.3	693.6
260	188	86.6	6.3	1.9	790.9	750.2
270	197	91.5	6.1	1.9	852.9	809.0
280	206	96.7	5.9	1.8	917.3	870.0
290	216	102.1	5.7	1.7	984.0	933.3
300	226	107.8	5.5	1.7	1053.0	998.8
310	237	113.9	5.3	1.6	1124.4	1066.5
320	248	120.3	5.1	1.5	1198.1	1136.4
330	261	127.0	4.8	1.5	1274.1	1208.5
340	273	134.1	4.6	1.4	1352.5	1282.9
350	287	141.6	4.4	1.3	1433.3	1359.4
360	301	149.5	4.2	1.3	1516.3	1438.2
370	316	157.9	4.0	1.2	1601.7	1519.2
380	332	166.7	3.7	1.1	1689.5	1602.5
390	349	176.1	3.5	1.1	1779.6	1687.9
400	367	186.0	3.3	1.0	1872.0	1775.6
410	386	196.4	3.1	0.9	1966.8	1865.5
420	405	207.5	2.8	0.9	2063.9	1957.6
430	427	219.2	2.6	0.8	2163.3	2051.9
440	449	231.6	2.3	0.7	2265.1	2148.5
450	472	244.7	2.1	0.6	2369.3	2247.2
460	497	258.5	1.8	0.6	2475.7	2348.2
470	524	273.2	1.6	0.5	2584.5	2451.4
480	552	288.7	1.3	0.4	2695.7	2556.9
490	581	305.0	1.0	0.3	2809.2	2664.5
500	612	322.3	0.8	0.2	2925.0	2774.4
510	645	340.4	0.5	0.1	3043.2	2886.4

520	679	359.5	0.2	0.1	3163.7	3000.8
530	715	379.4	0.0	0.0	3286.5	3117.3

The drop of the upper level to the top of the burning item and the rise in the upper level temp. indicate vitiation of the combustion air with fire products. It is likely that the burning rate will be depressed possibly smothered.

11 : GRAPHICAL RESULTS FROM T² FIRE ANALYSES

The following pages give the graphical results for all the t² fire analyses undertaken. These are presented, grouped by fire growth rate.

Slow Fire Growth Rate

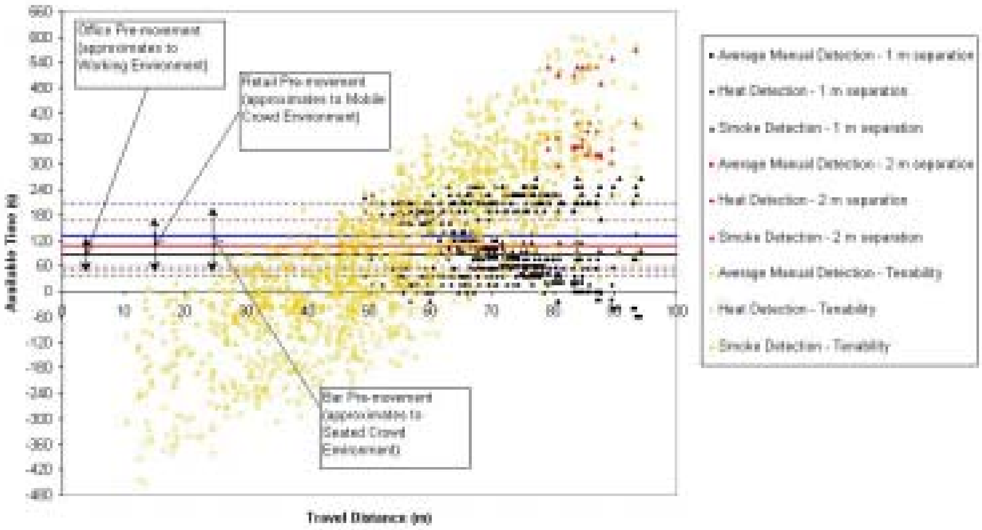

Figure 11.1 : Available Evacuation Time - Slow Fire Growth Rate

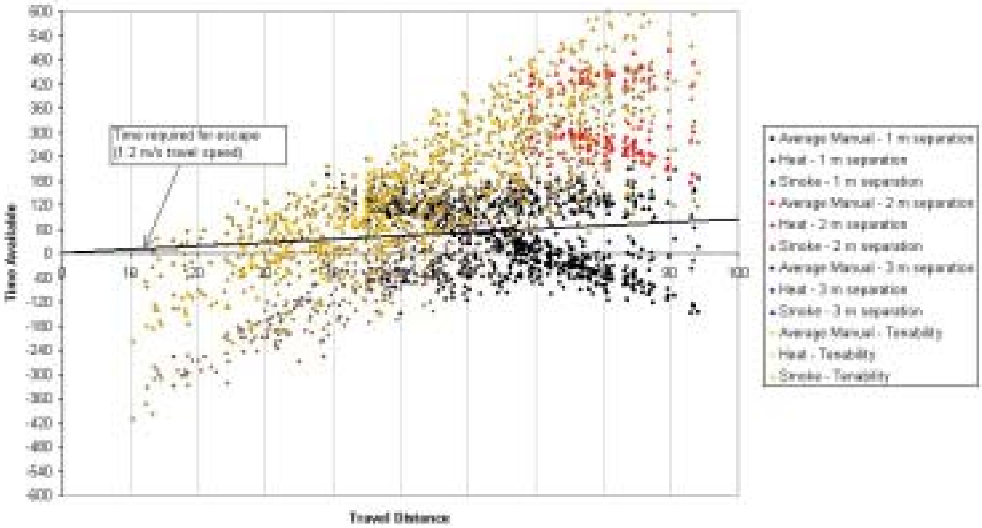

Figure 11.2 : Available Escape Time from Work Environment - Slow Fire Growth Rate

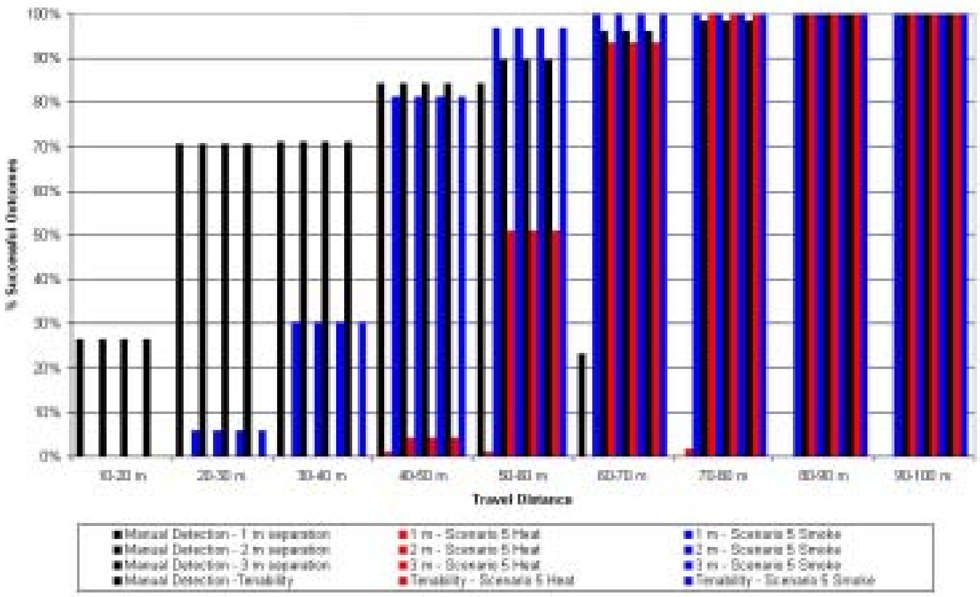

Figure 11.3 : Work Environment Escape Scenario Comparison – Slow Fire Growth Rate

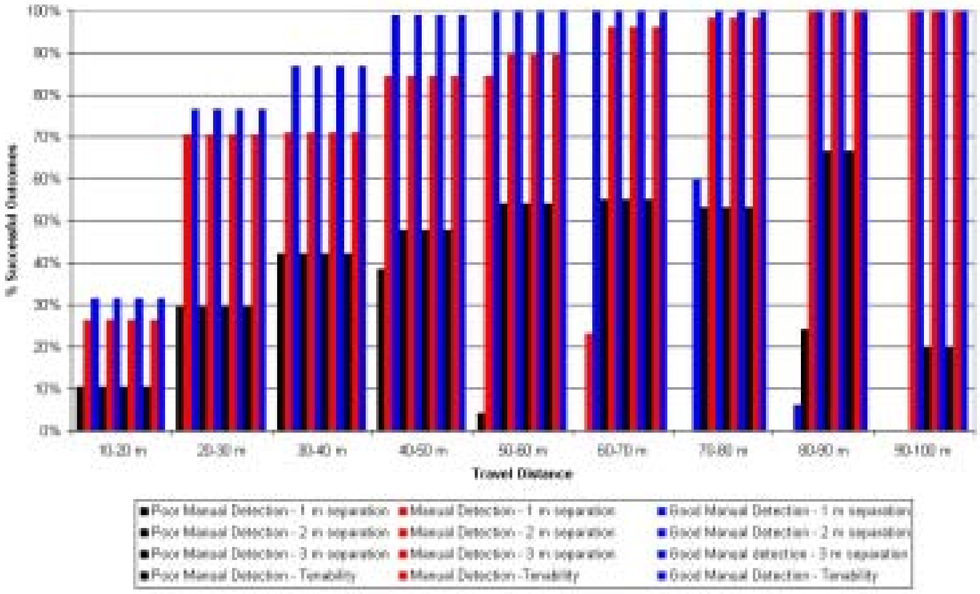

Figure 11.4 : Work Environment Escape Manual Detection Scenario Outcome Comparison – Slow Fire Growth Rate

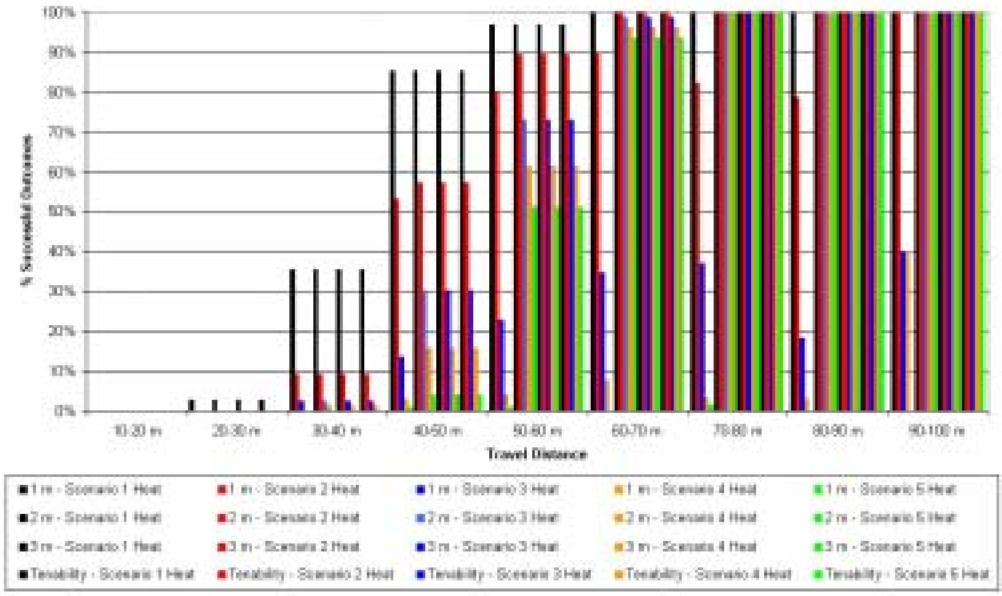

Figure 11.5 : Work Environment Escape Heat Detection Scenario Outcome Comparison - Slow Fire Growth Rate

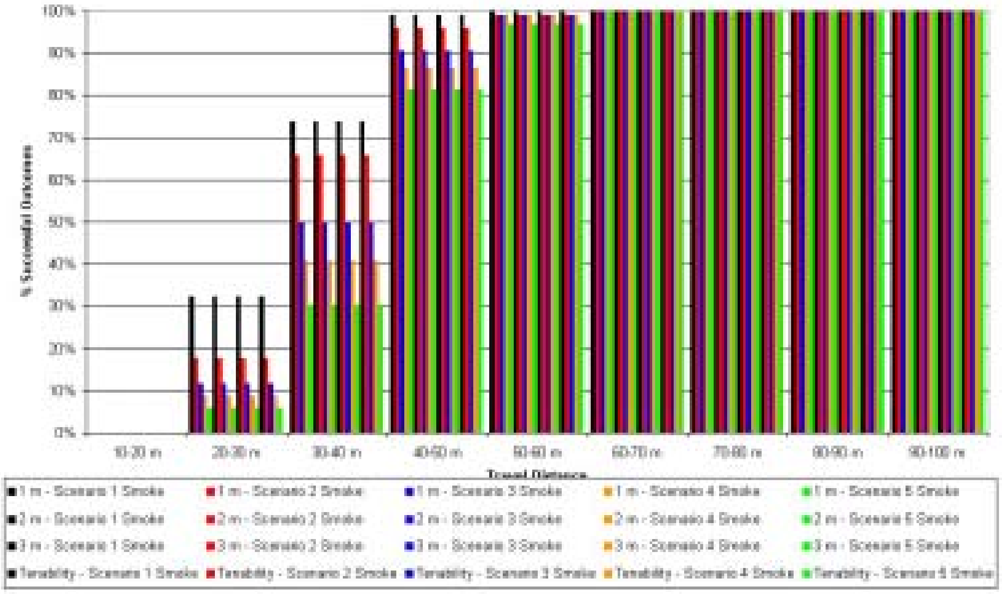

Figure 11.6 : Work Environment Escape Smoke Detection Scenario Outcome Comparison - Slow Fire Growth Rate

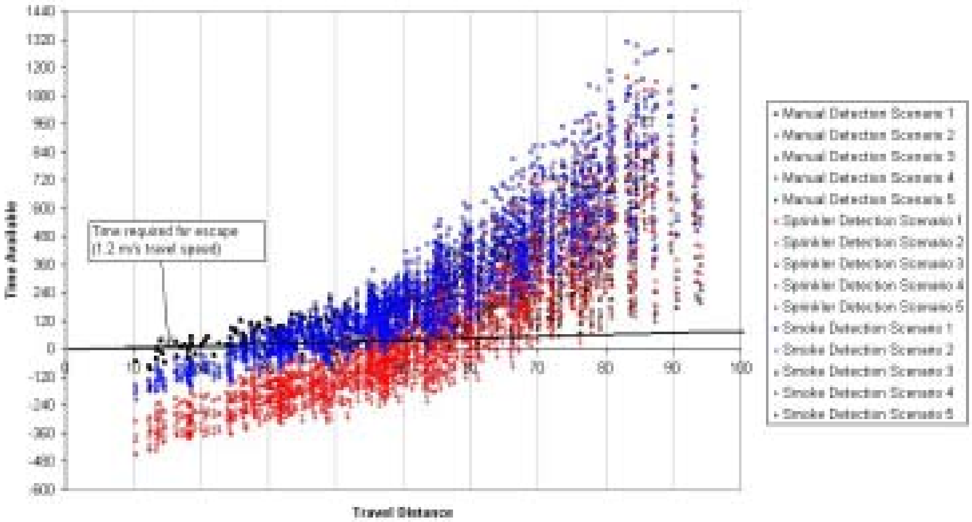

Figure 11.7 : Work Environment Available Escape Time with Sprinkler Protection - Slow Fire Growth Rate

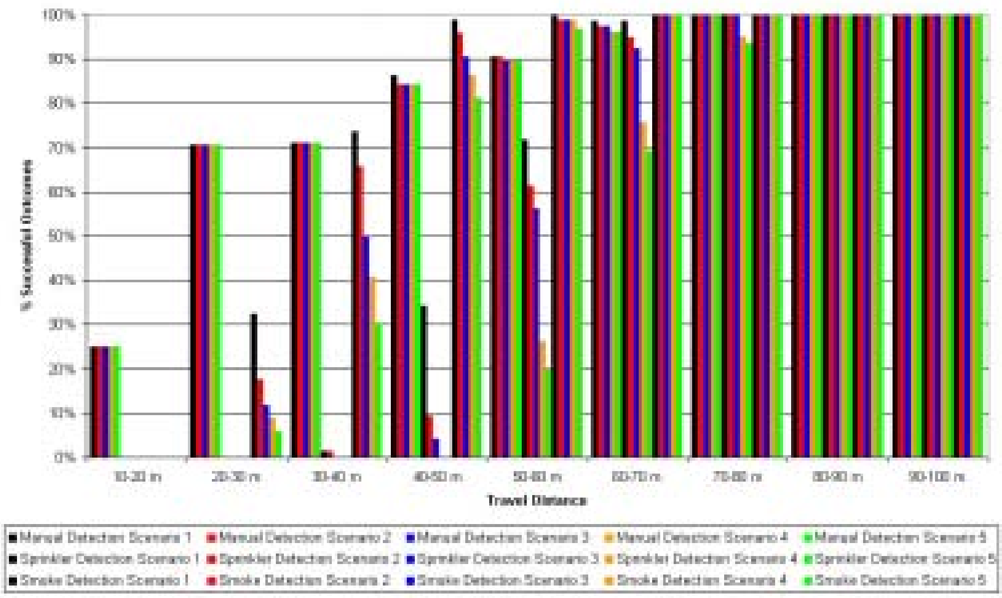

Figure 11.8 : Work Environment Escape Sprinkler Protection Scenario Outcome Comparison - Slow Fire Growth Rate

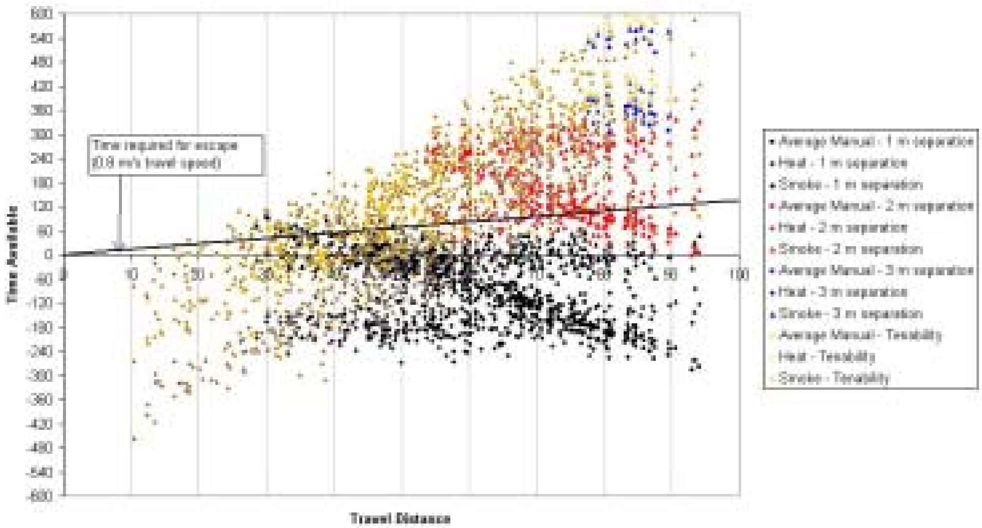

Figure 11.9 : Mobile Crowd Environment - Available Escape Time

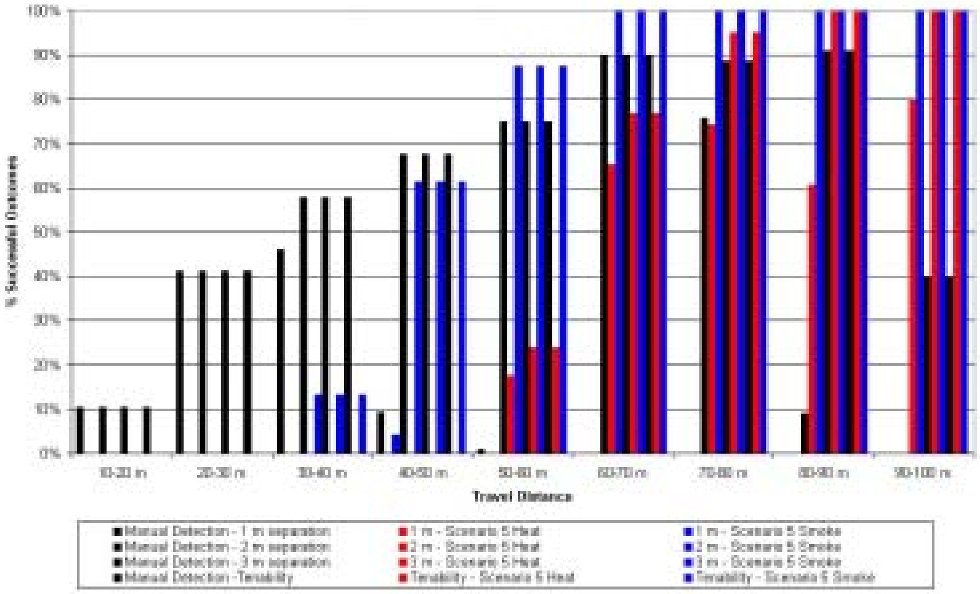

Figure 11.10 : Mobile Crowd Environment Escape Scenario Comparison - Slow Fire Growth Rate

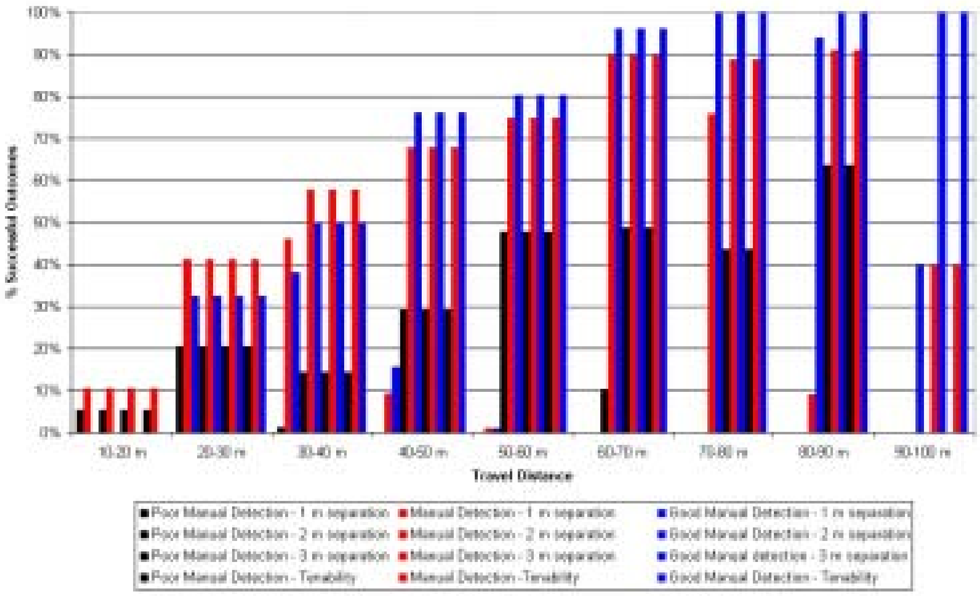

Figure 11.11 : Mobile Crowd Environment Manual Detection Escape Scenario Outcome Comparison - Slow Fire Growth Rate

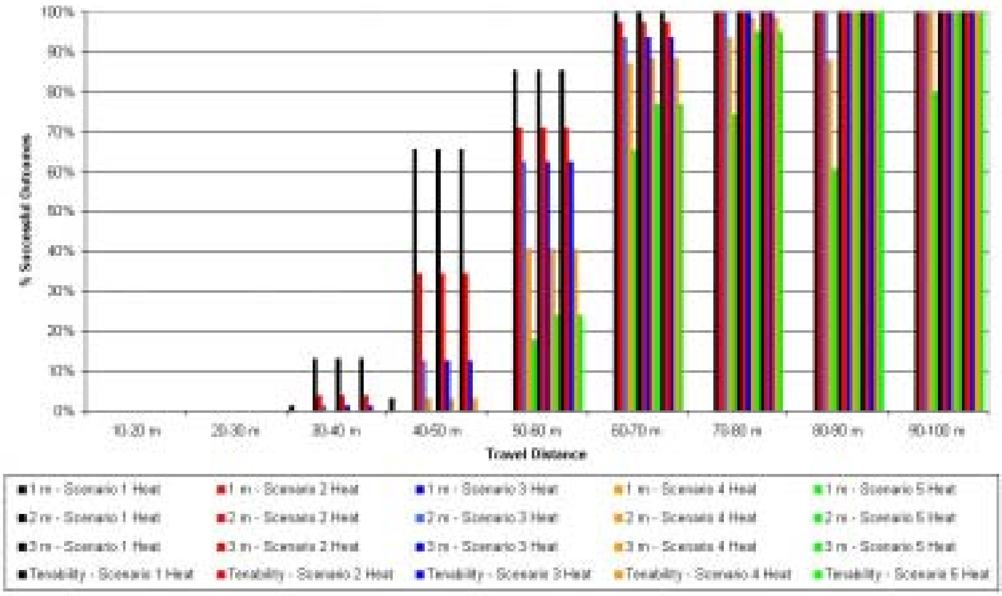

Figure 11.12 : Mobile Crowd Environment Heat Detection Escape Scenario Outcome Comparison - Slow Fire Growth Rate

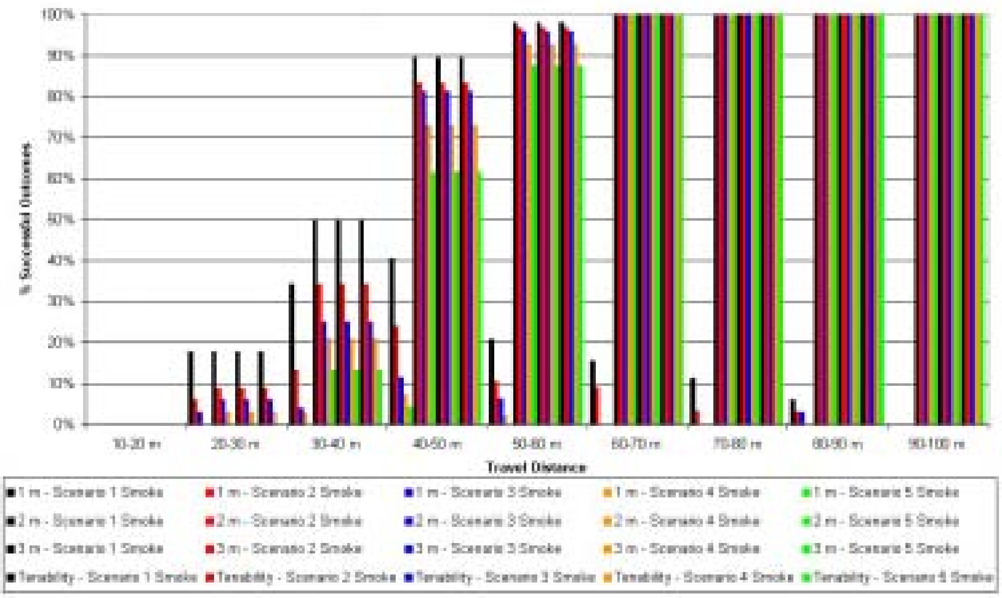

Figure 11.13 : Mobile Crowd Environment Smoke Detection Escape Scenario Outcome Comparison - Slow Fire Growth Rate

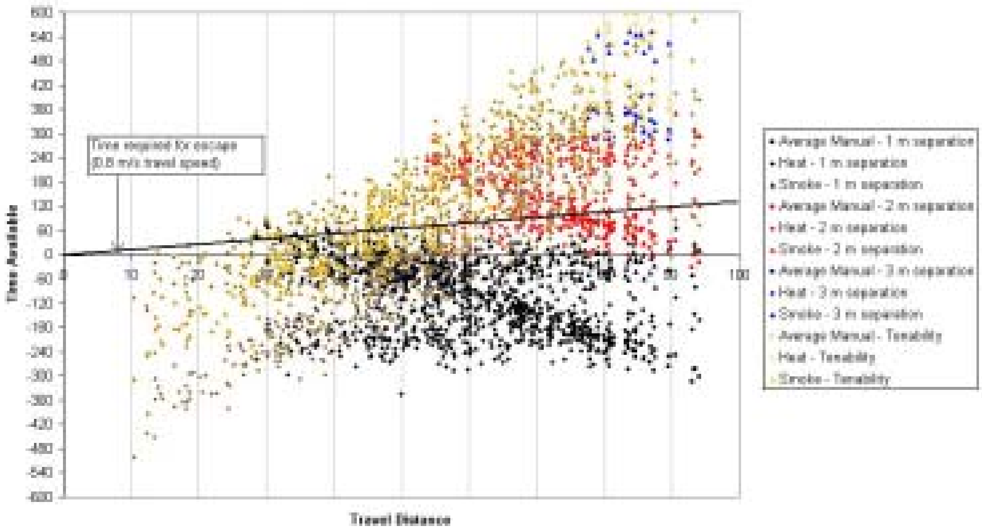

Figure 11.14 : Seated Crowd Environment Available Escape Time - Slow Fire Growth Rate

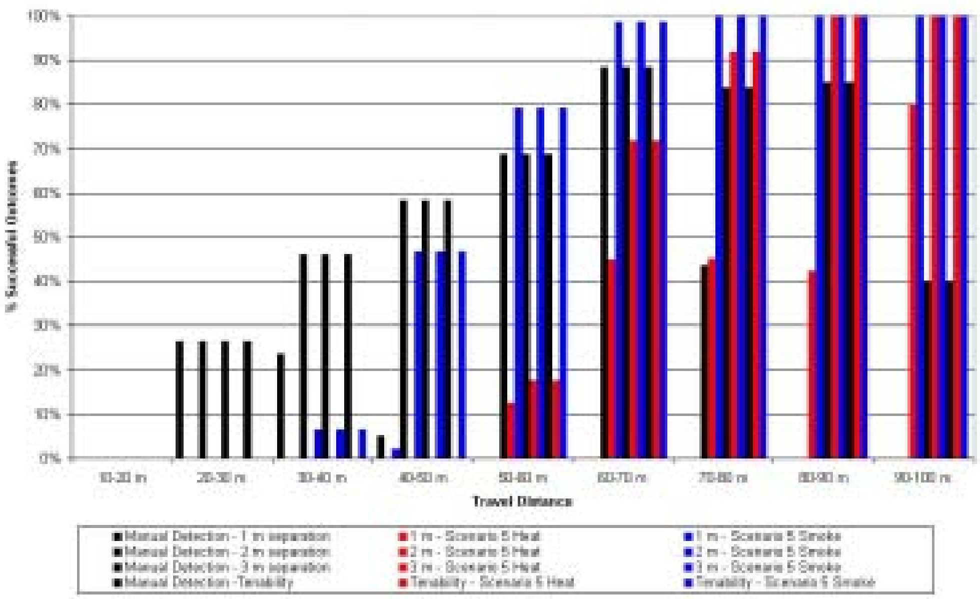

Figure 11.15 : Seated Crowd Environment Escape Scenario Outcome Comparison - Slow Fire Growth Rate

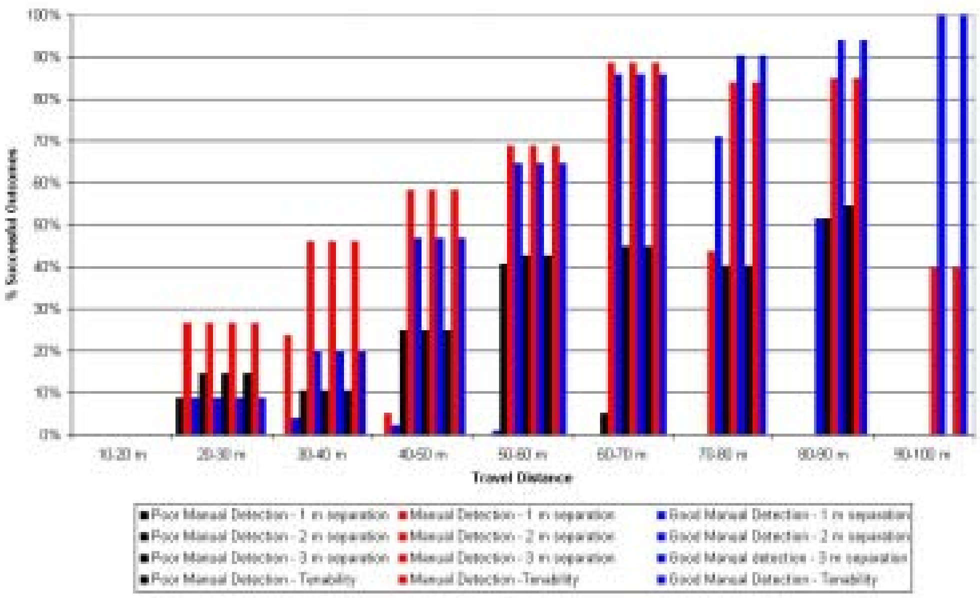

Figure 11.16 : Seated Crowd Environment Manual Detection Escape Scenario Outcome Comparison - Slow Fire Growth Rate

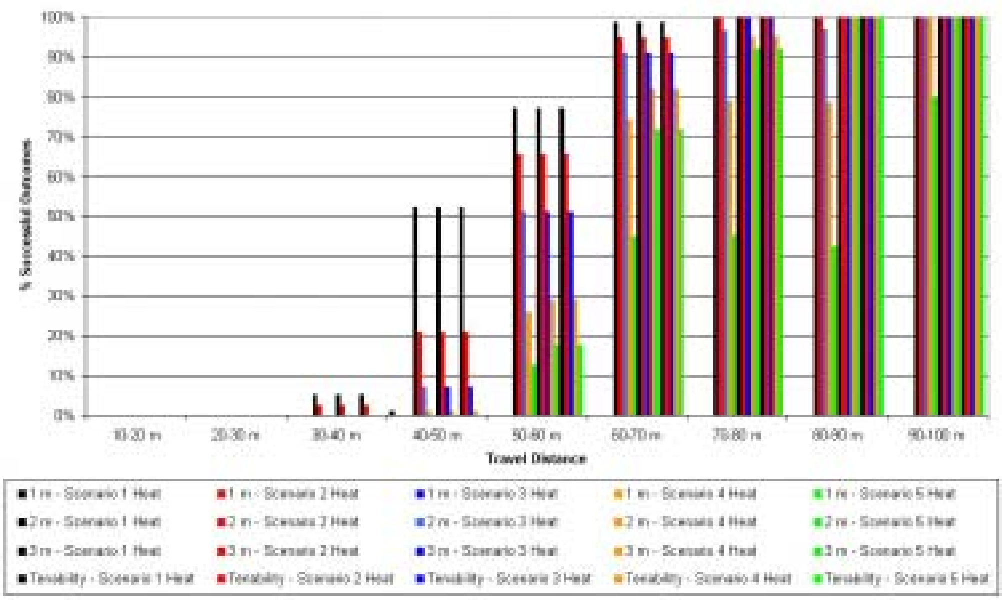

Figure 11.17 : Seated Crowd Environment Heat Detection Escape Scenario Outcome Comparison - Slow Fire Growth Rate

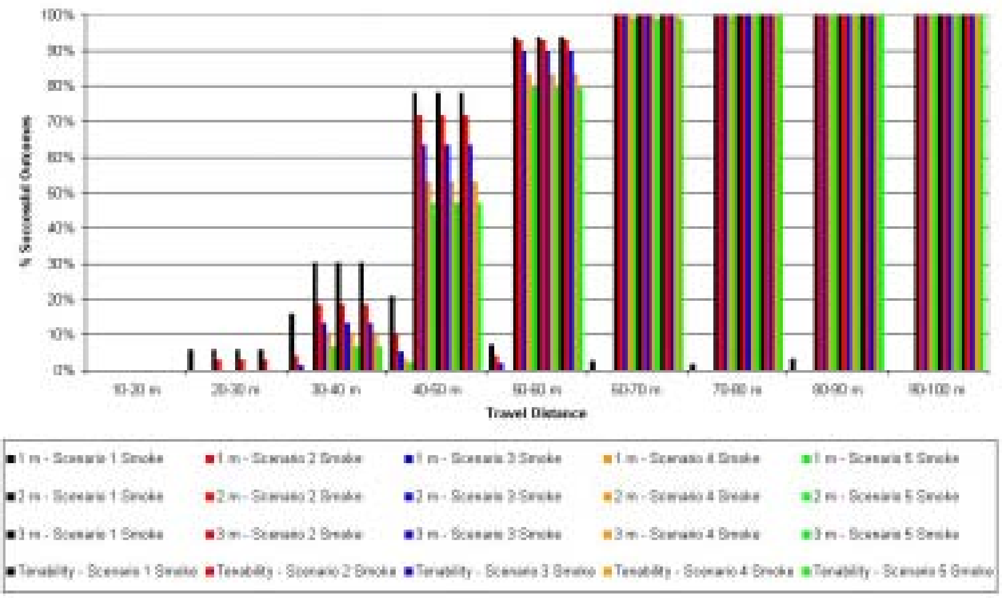

Figure 11.18 : Seated Crowd Environment Smoke Detection Escape Scenario Outcome Comparison - Slow Fire Growth Rate

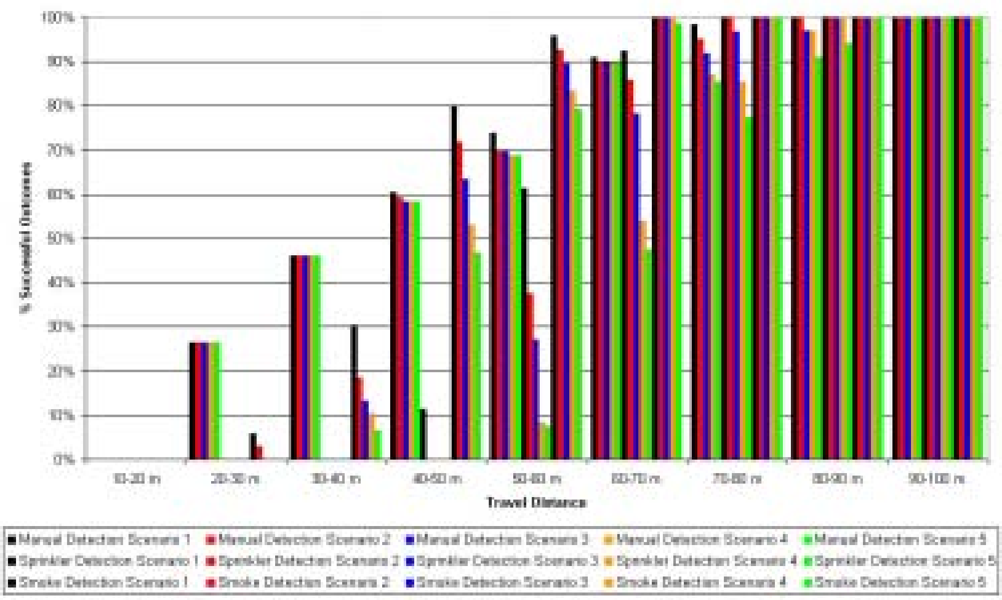

Figure 11.19 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison - Slow Fire Growth Rate

Medium Fire Growth Rate

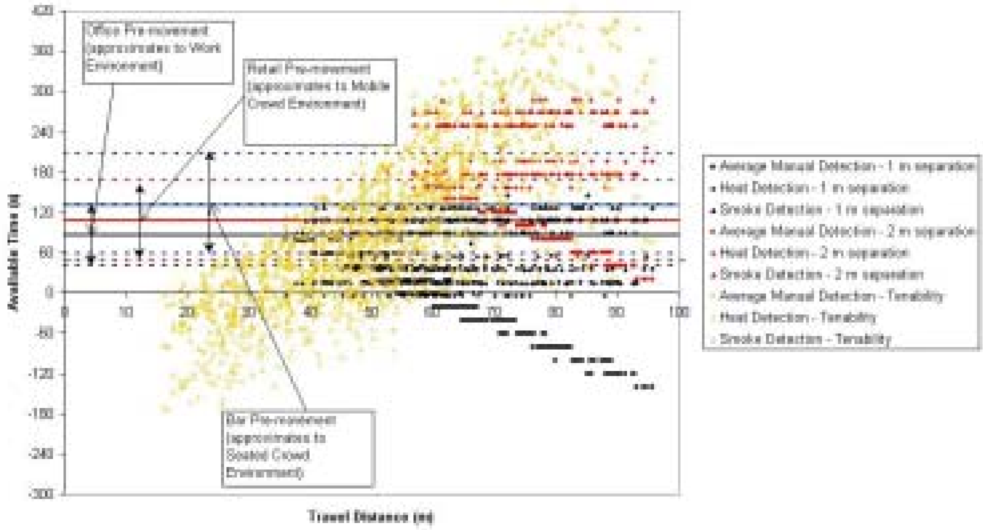

Figure 11.20 : Available Evacuation Time - Medium Fire Growth Rate

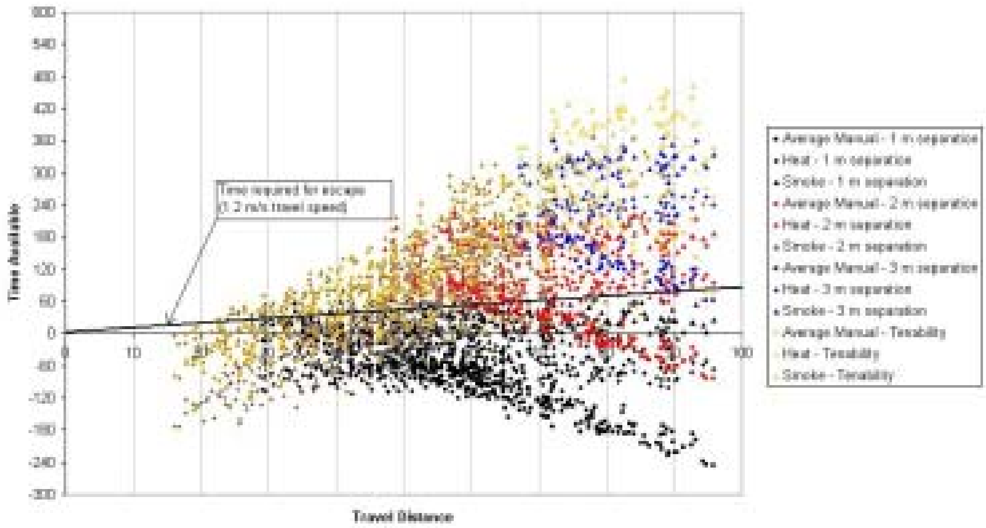

Figure 11.21 : Available Escape Time from Work Environment - Medium Fire Growth Rate

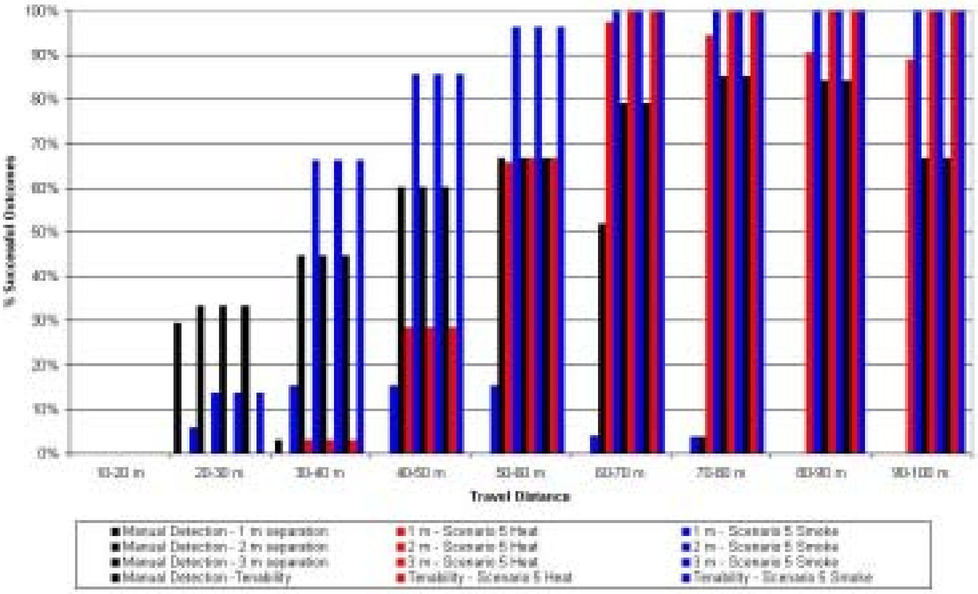

Figure 11.22 : Work Environment Escape Scenario Outcome Comparison - Medium Fire Growth Rate

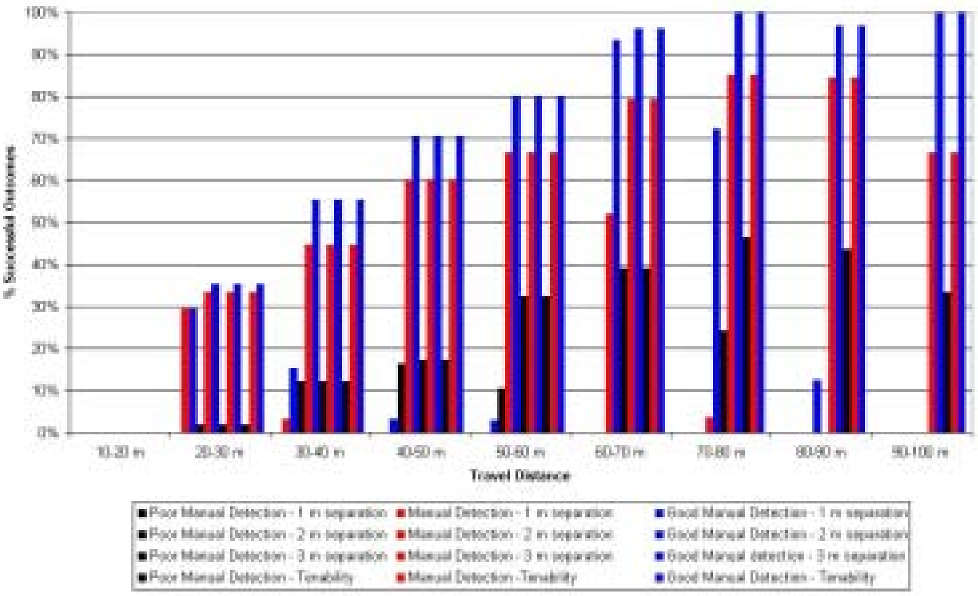

Figure 11.23 : Work Environment Manual Detection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

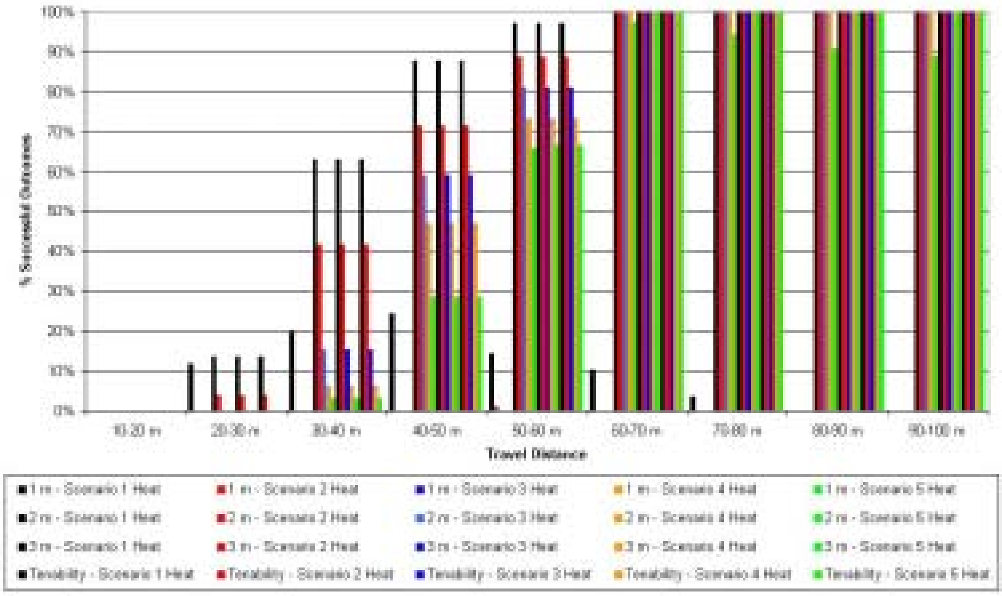

Figure 11.24 : Work Environment Heat Detection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

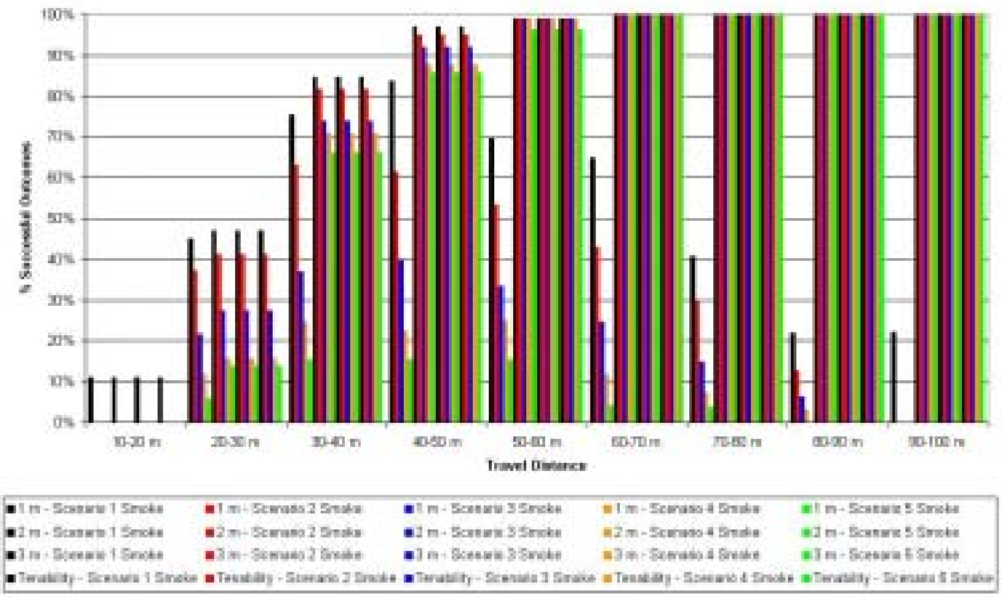

Figure 11.25 : Work Environment Smoke Detection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

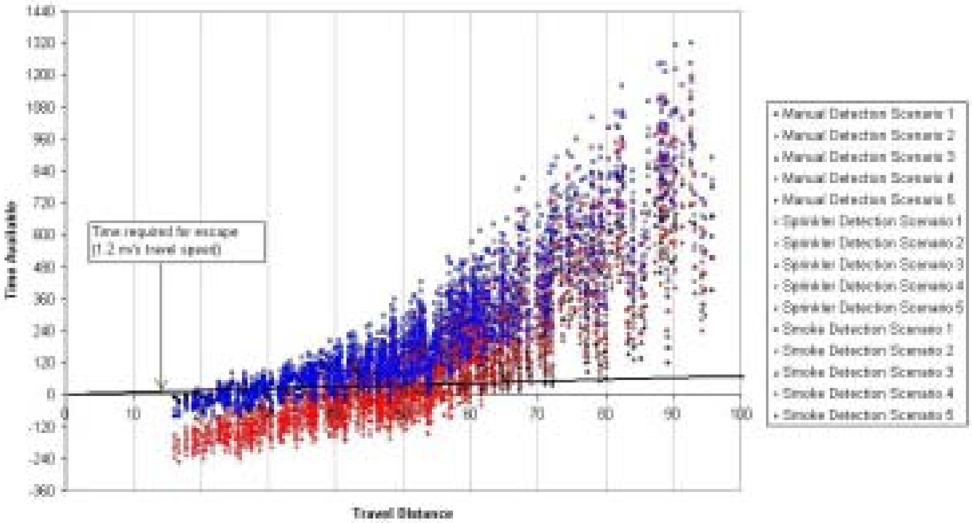

Figure 11.26 : Available Escape Time from Sprinkler Protected Work Environment - Medium Fire Growth Rate

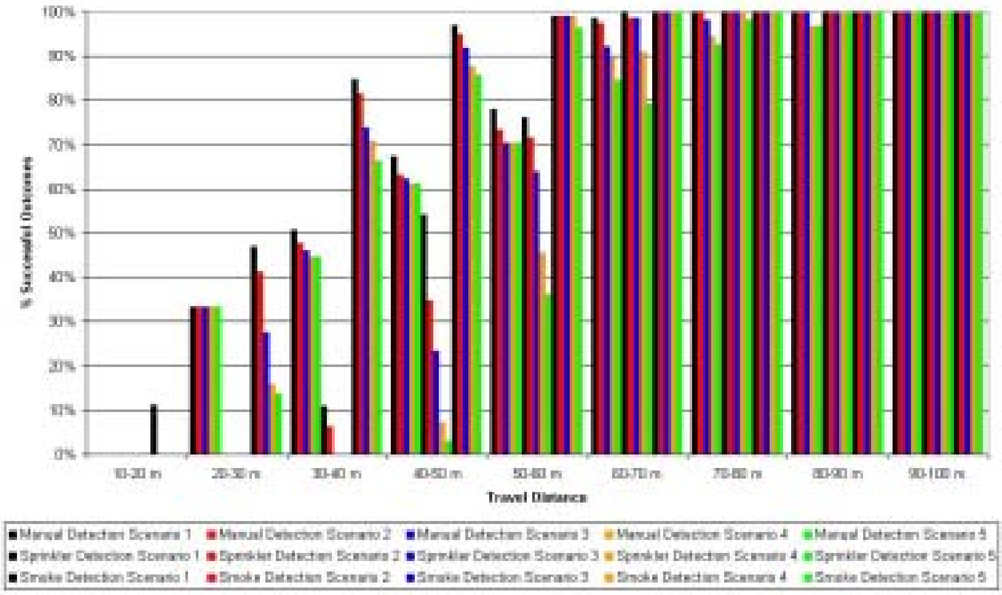

Figure 11.27 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

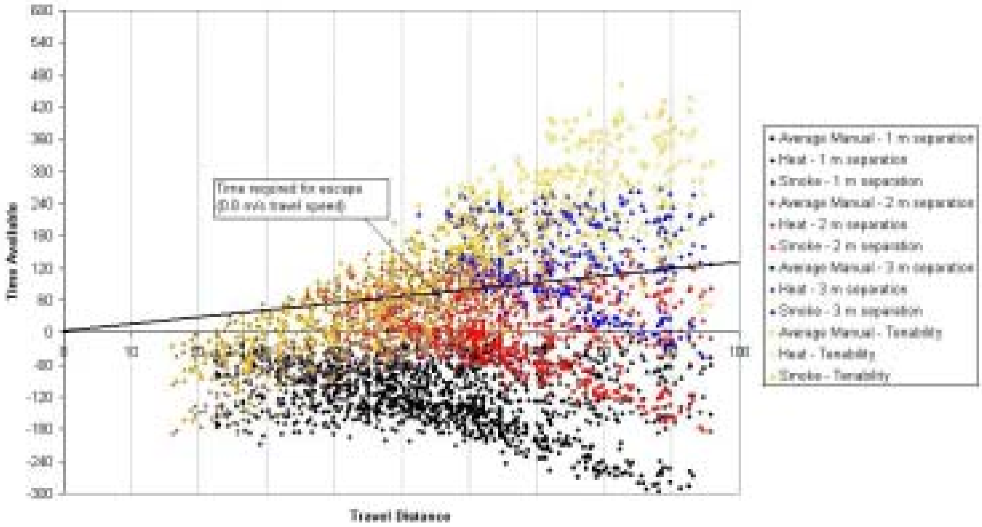

Figure 11.28 : Available Escape Time from Mobile Crowd Occupancy - Medium Fire Growth Rate

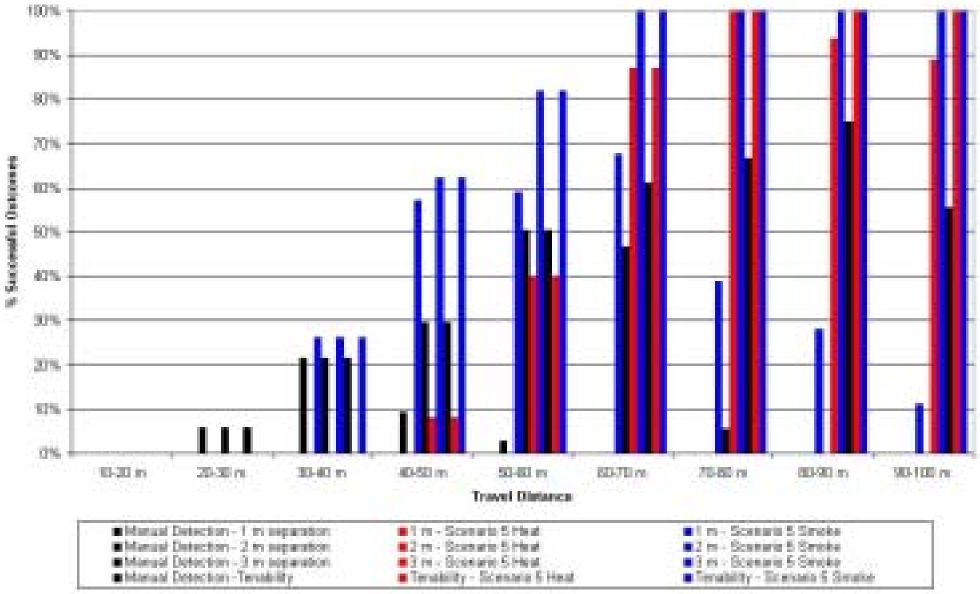

Figure 11.29 : Mobile Crowd Environment Escape Scenario Outcome Comparison - Medium Fire Growth Rate

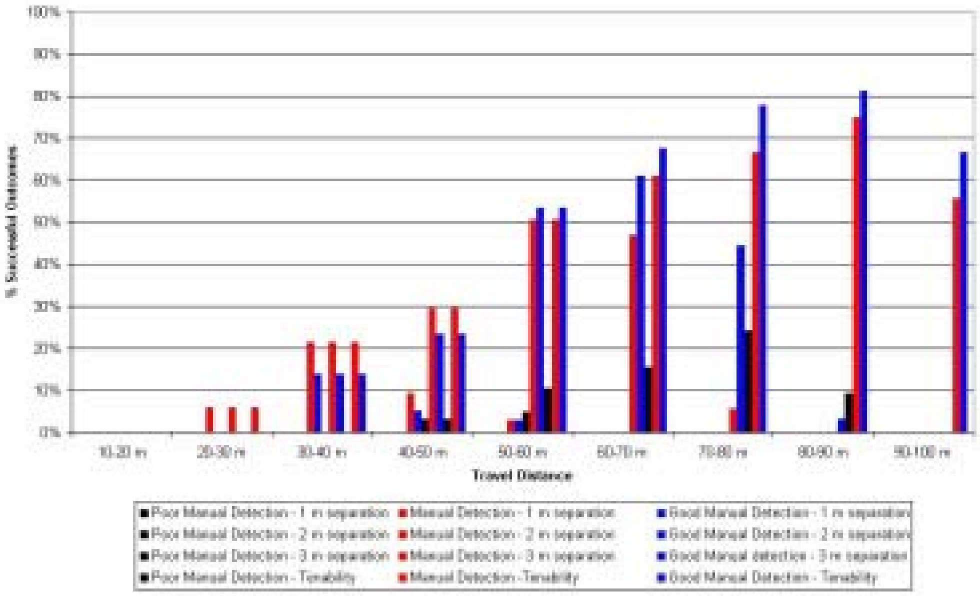

Figure 11.30 : Mobile Crowd Environment Manual Detection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

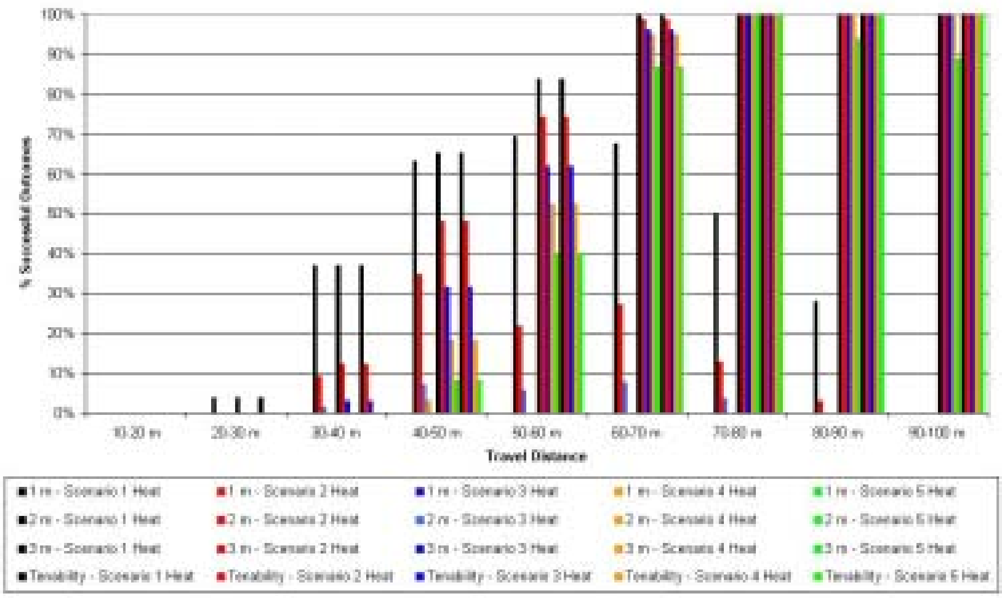

Figure 11.31 : Mobile Crowd Environment Heat Detection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

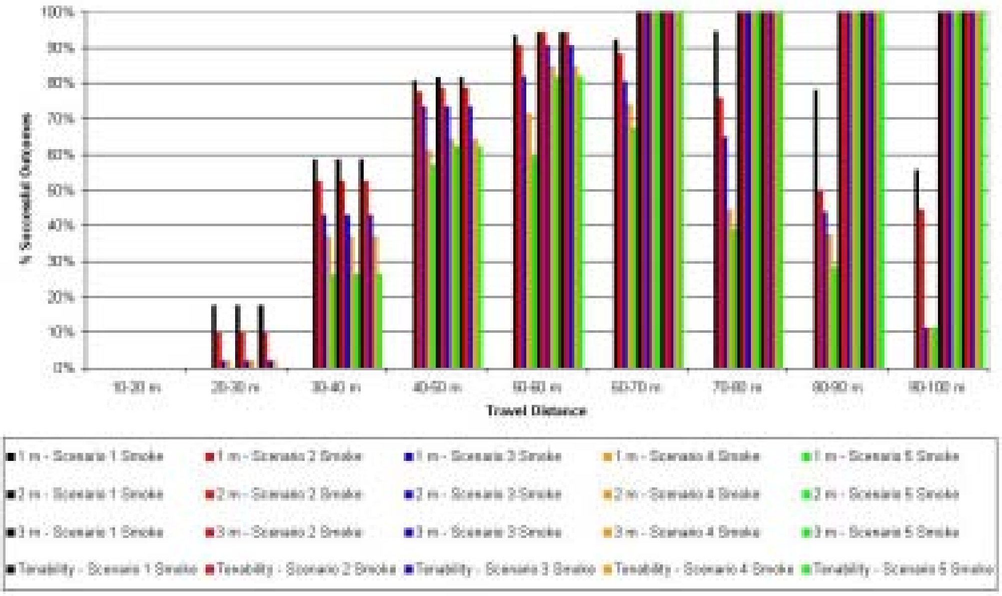

Figure 11.32 : Mobile Crowd Environment Smoke Detection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

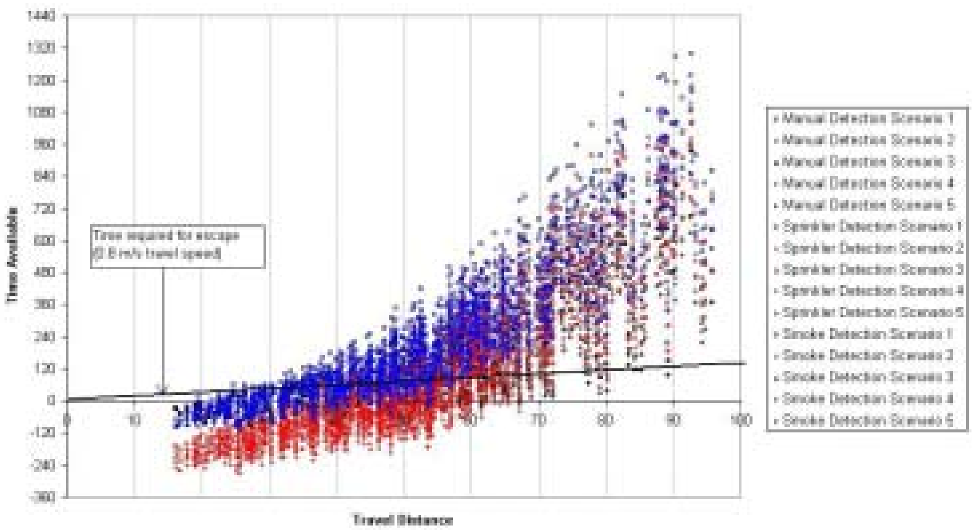

Figure 11.33 : Available Escape Time from Mobile Crowd Environment with Sprinkler Protection - Medium Fire Growth Rate

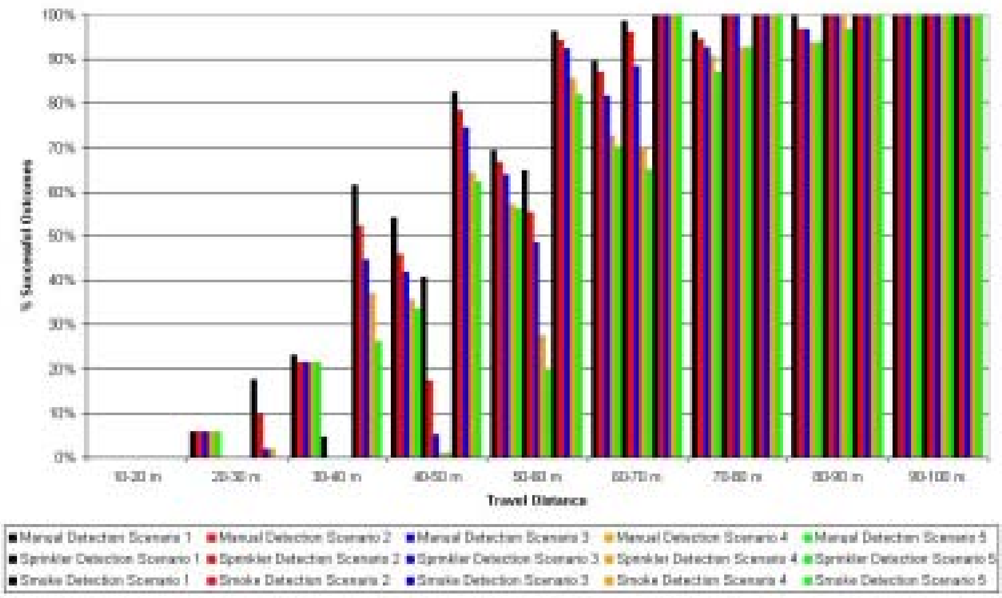

Figure 11.34 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison -Medium Fire Growth Rate

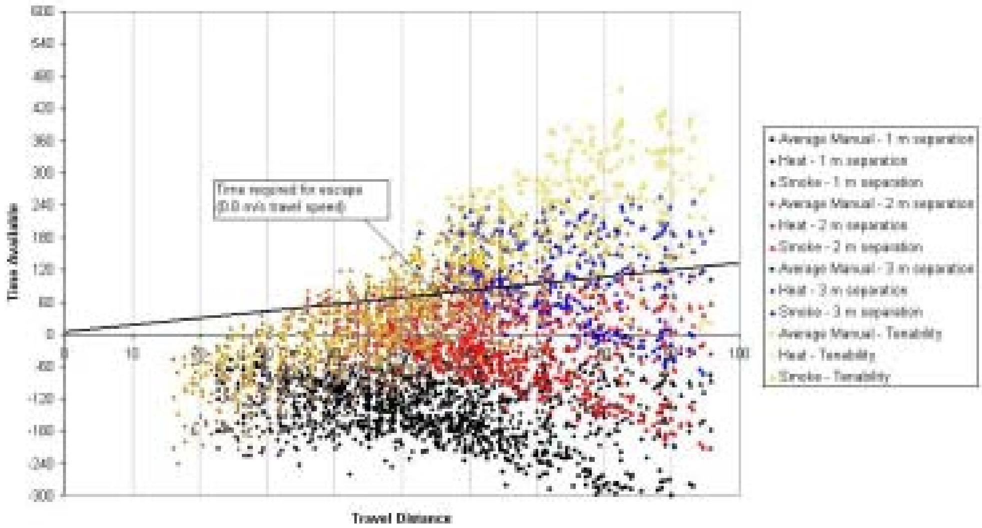

Figure 11.35 : Available Escape Time from Seated Crowd Environment - Medium Fire Growth Rate

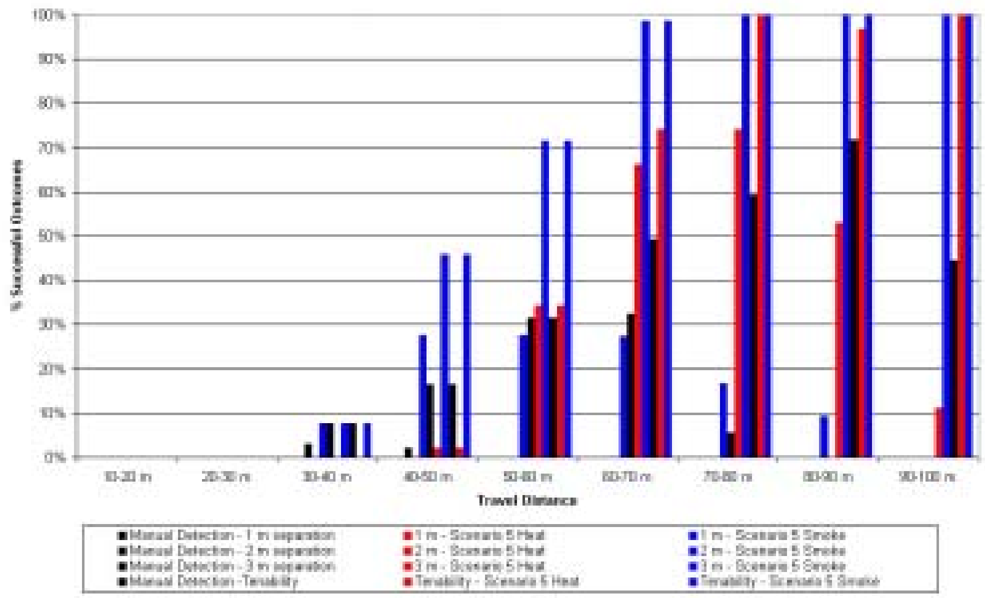

Figure 11.36 : Seated Crowd Environment Escape Scenario Outcome Comparison - Medium Fire Growth Rate

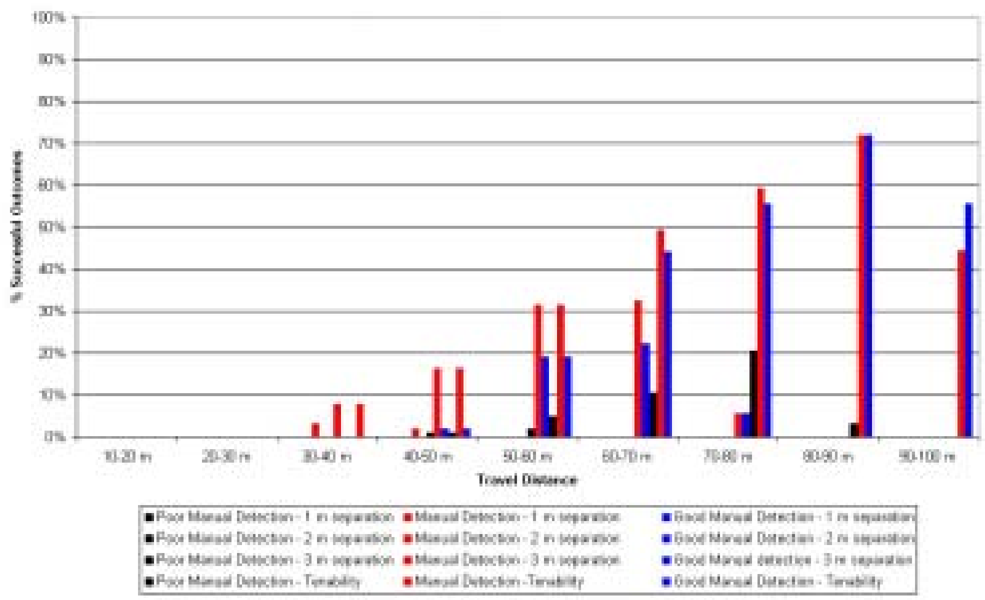

Figure 11.37 : Seated Crowd Environment Manual Detection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

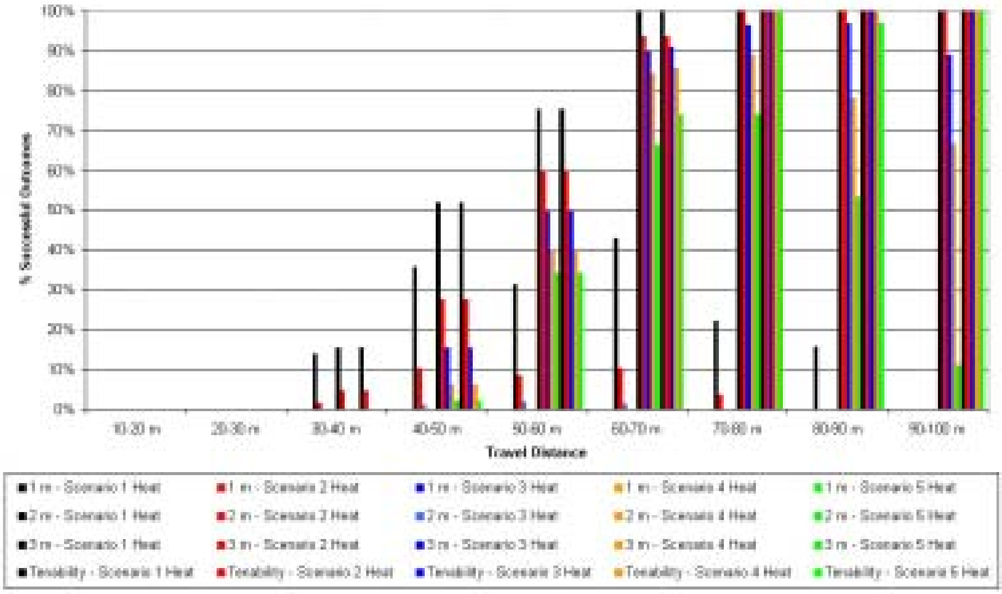

Figure 11.38 : Seated Crowd Environment Heat Detection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

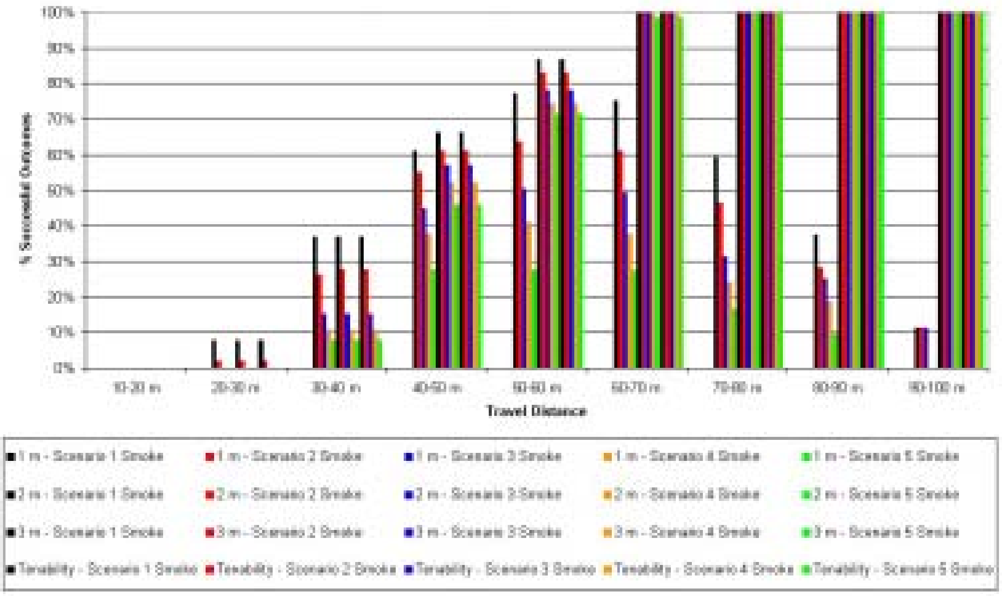

Figure 11.39 : Seated Crowd Environment Smoke Detection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

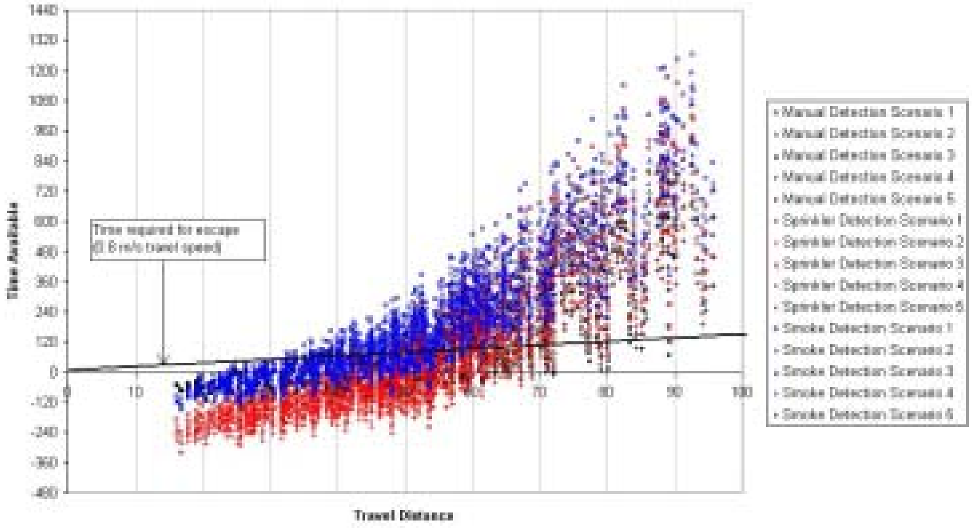

Figure 11.40 : Available Escape Time from Sprinkler Protected Seated Crowd Environment - Medium Fire Growth Rate

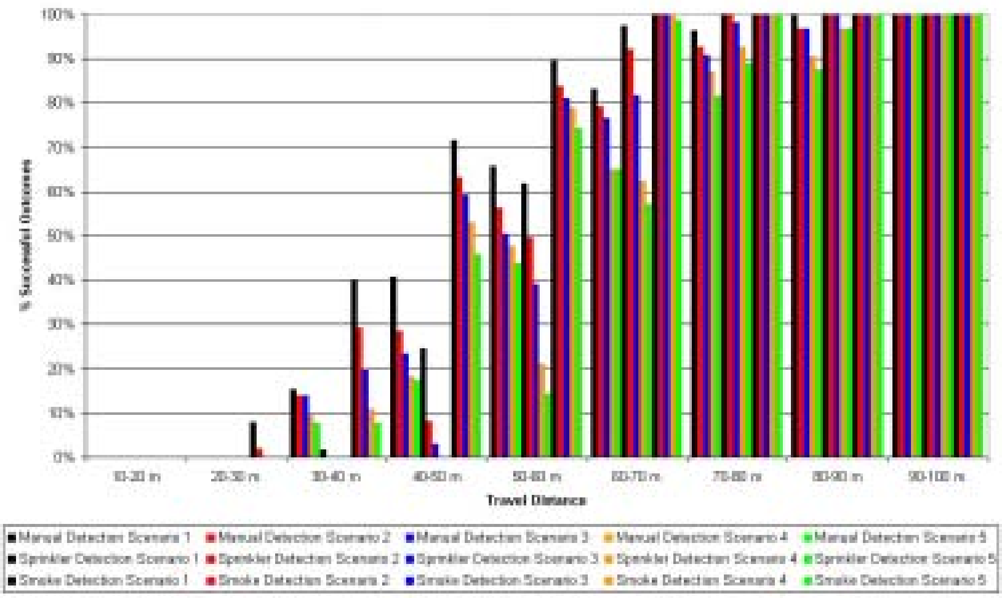

Figure 11.41 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison - Medium Fire Growth Rate

Fast Fire Growth Rate

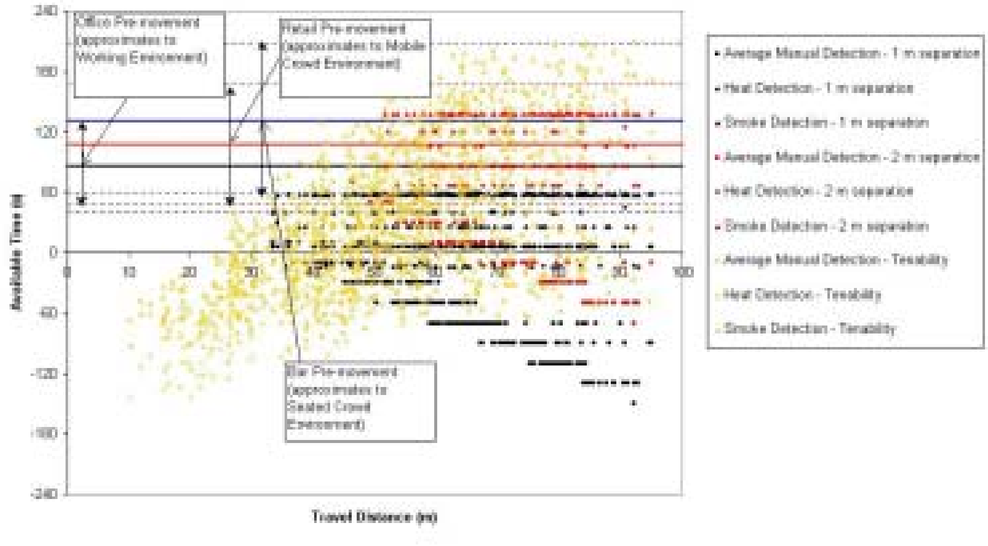

Figure 11.42 : Available Escape Time - Fast Fire Growth Rate

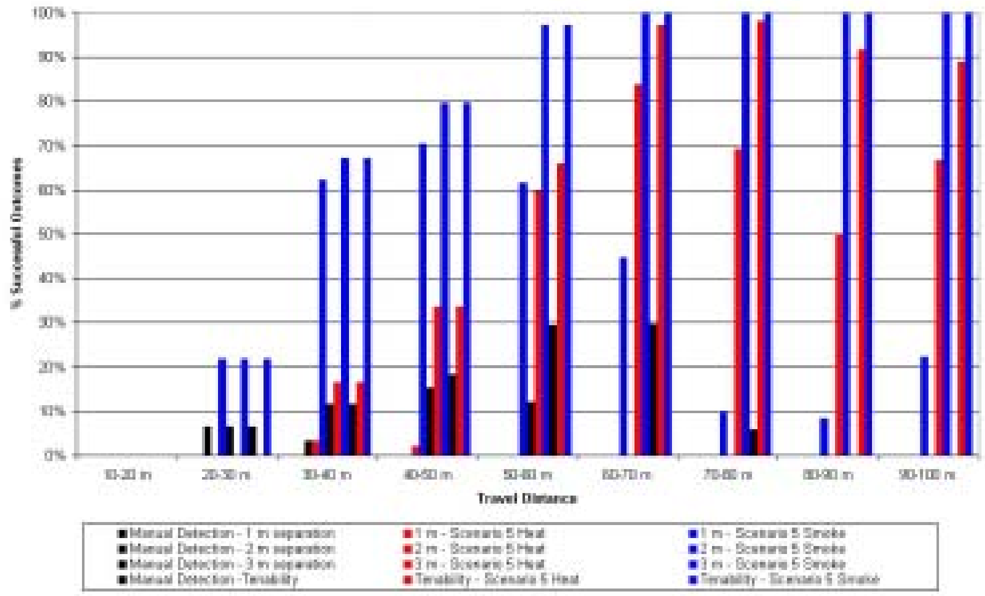

Figure 11.43 : Work Environment Escape Scenario Outcome - Fast Fire Growth Rate

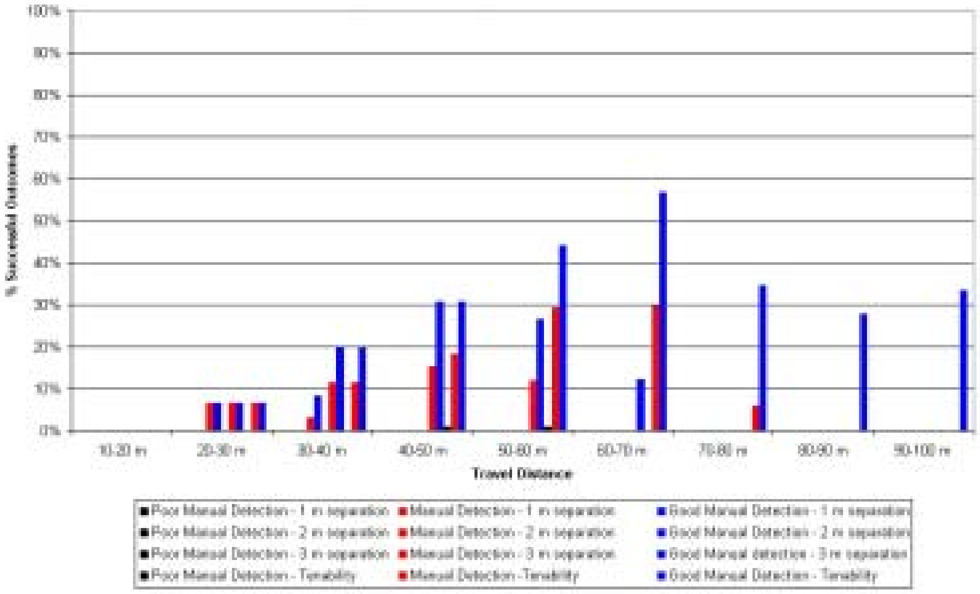

Figure 11.44 : Work Environment Manual Detection Escape Scenario Outcome Comparison - Fast Fire Growth Rate

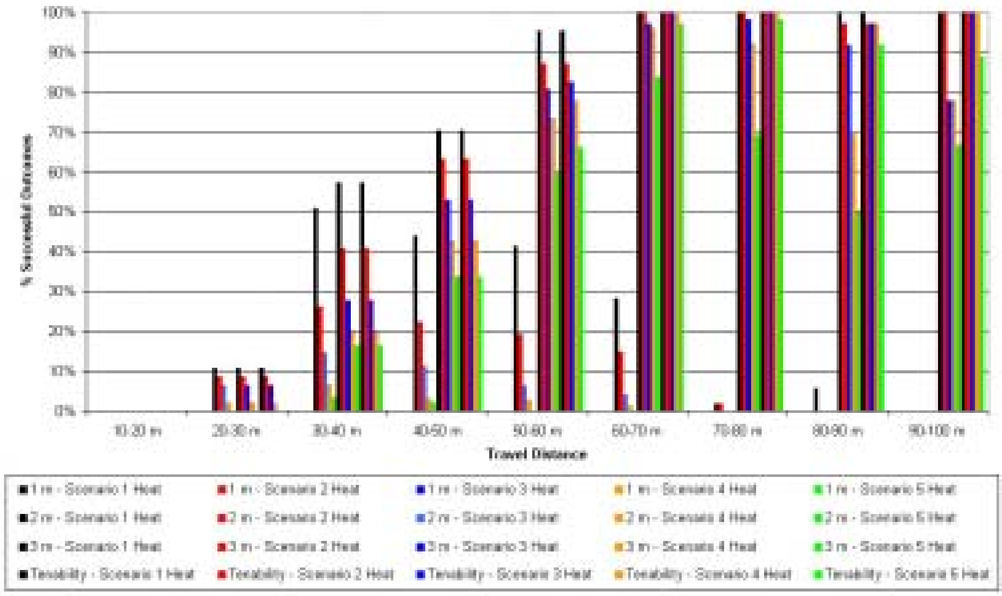

Figure 11.45 : Work Environment Heat Detection Escape Scenario Outcome Comparison - Fast Fire Growth Rate

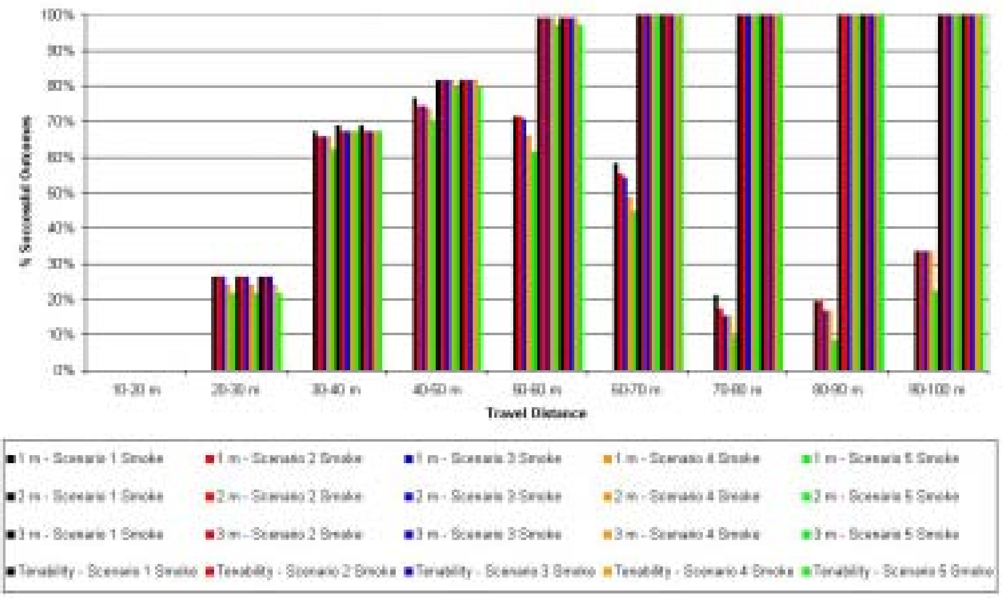

Figure 11.46 : Work Environment Smoke Detection Escape Scenario Outcome Comparison - Fast Fire Growth Rate

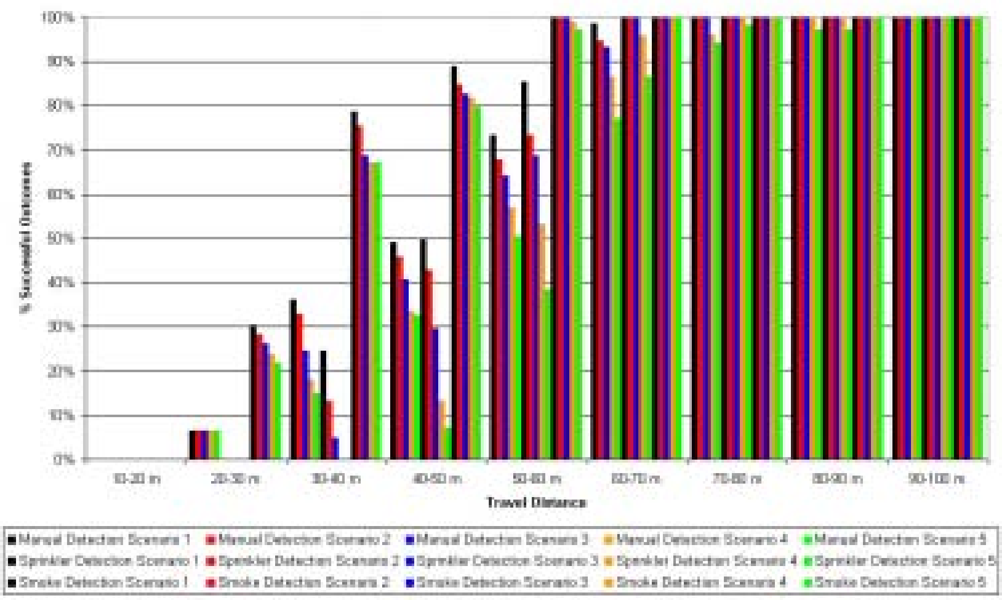

Figure 11.47 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison - Fast Fire Growth Rate

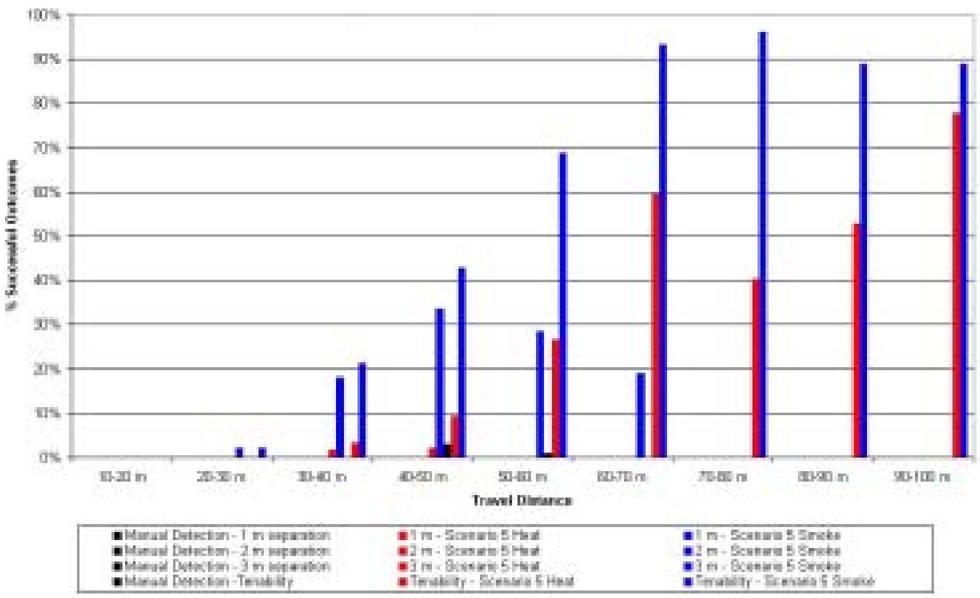

Figure 11.48 : Mobile Crowd Environment Escape Scenario Comparison - Fast Fire Growth Rate

A figure for the Mobile Crowd Environment Manual Detection Escape Scenario Outcome Comparison - Fast Fire Growth Rate has not been included as it shows no successful outcomes.

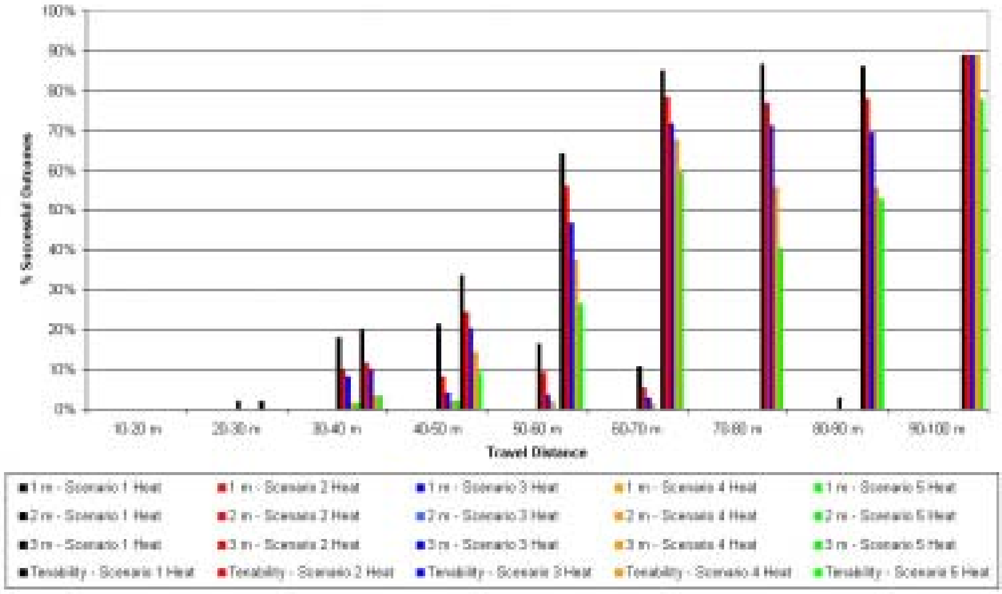

Figure 11.49 : Mobile Crowd Environment Heat Detection Escape Scenario Outcome Comparison- Fast Fire Growth Rate

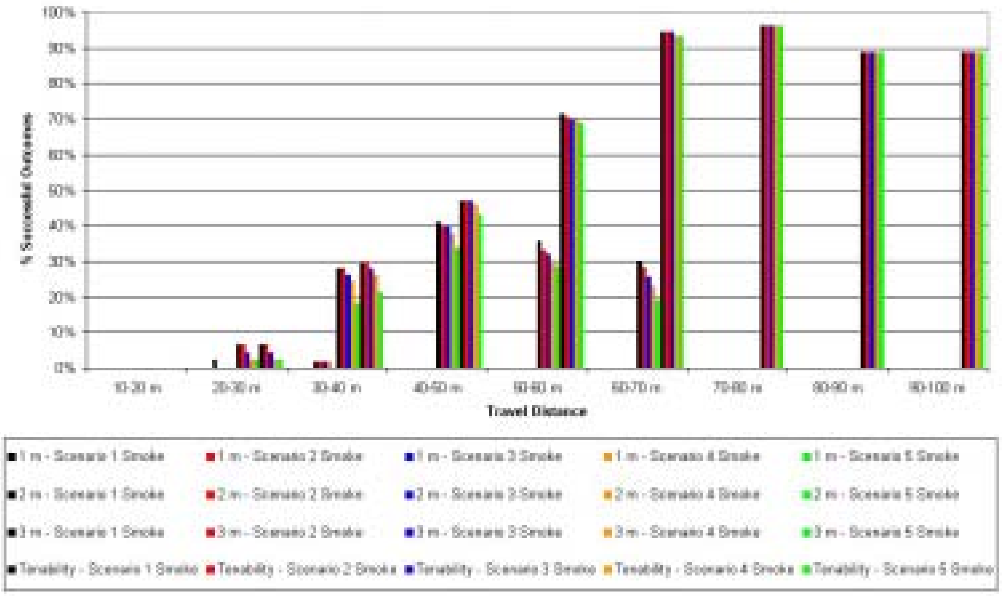

Figure 11.50 : Mobile Crowd Environment Smoke Detection Escape Scenario Outcome Comparison - Fast Fire Growth Rate

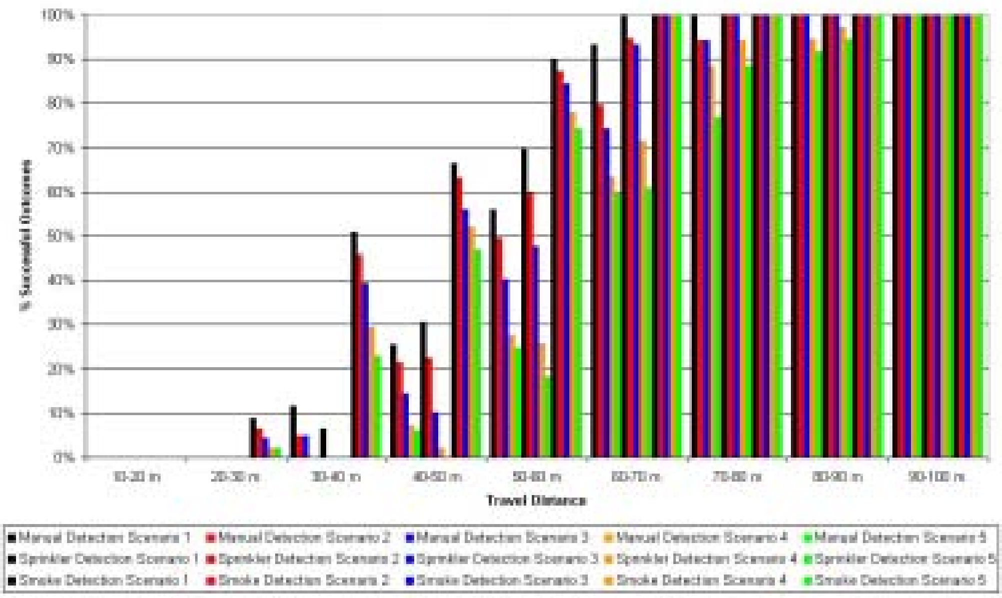

Figure 11.51 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison - Fast Fire Growth Rate

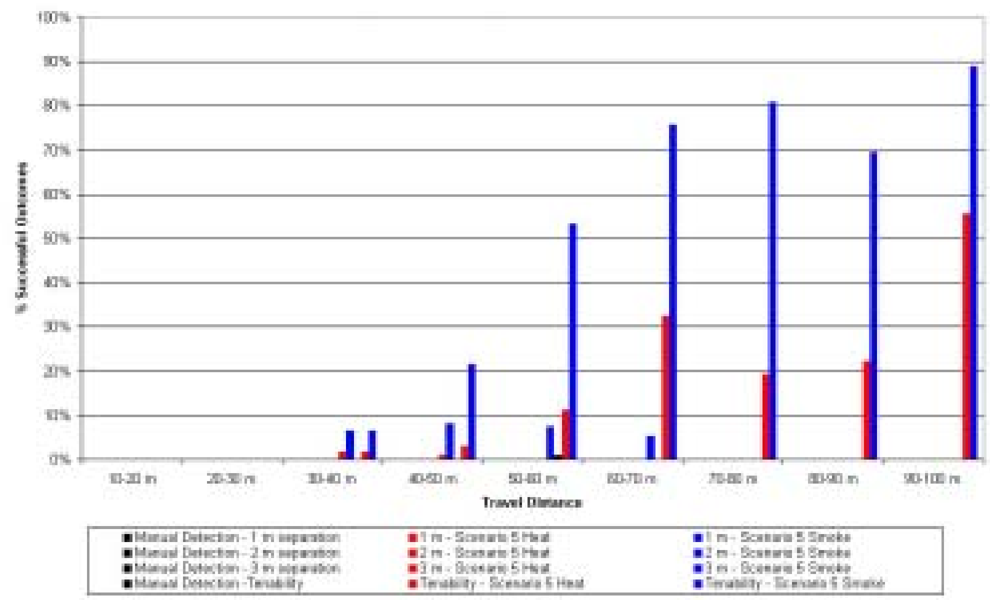

Figure 11.52 : Seated Crowd Environment Escape Scenario Outcome Comparison - Fast Fire Growth Rate

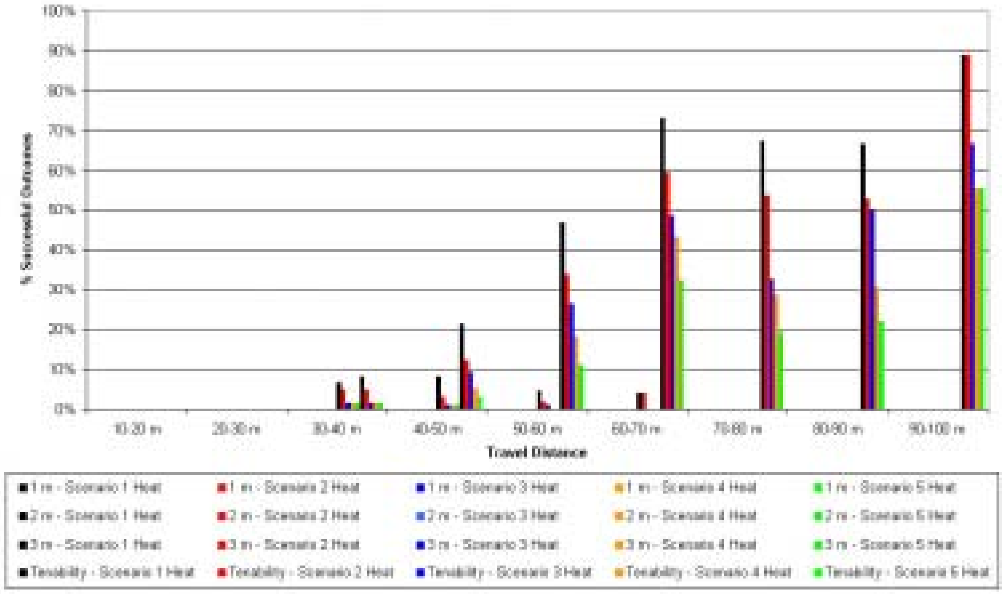

Figure 11.53 : Seated Crowd Environment Heat Detection Escape Scenario Outcome Comparison - Fast Fire Growth Rate

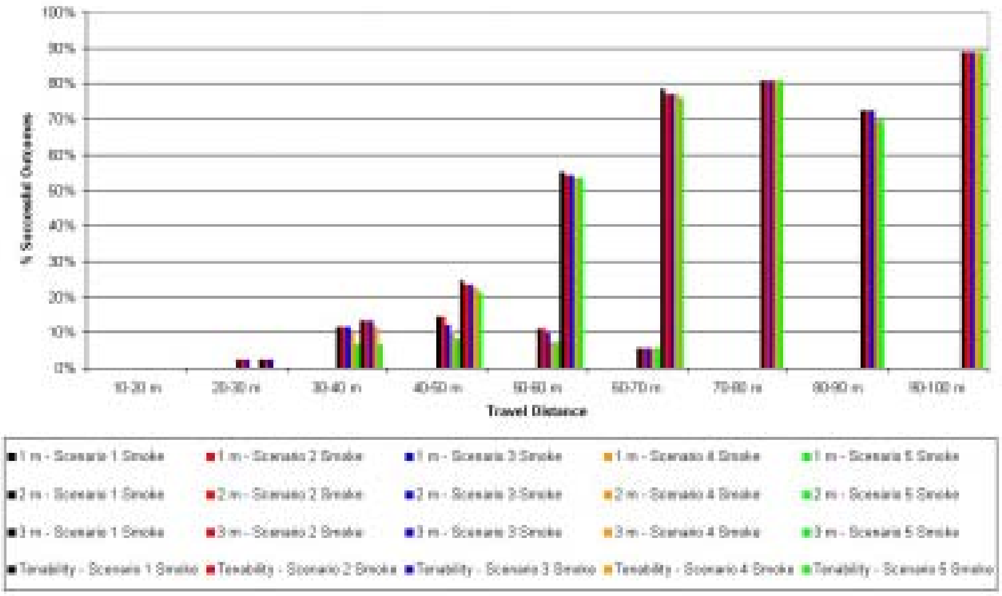

Figure 11.54 : Seated Crowd Environment Smoke Detection Escape Scenario Outcome Comparison - Fast Fire Growth Rate

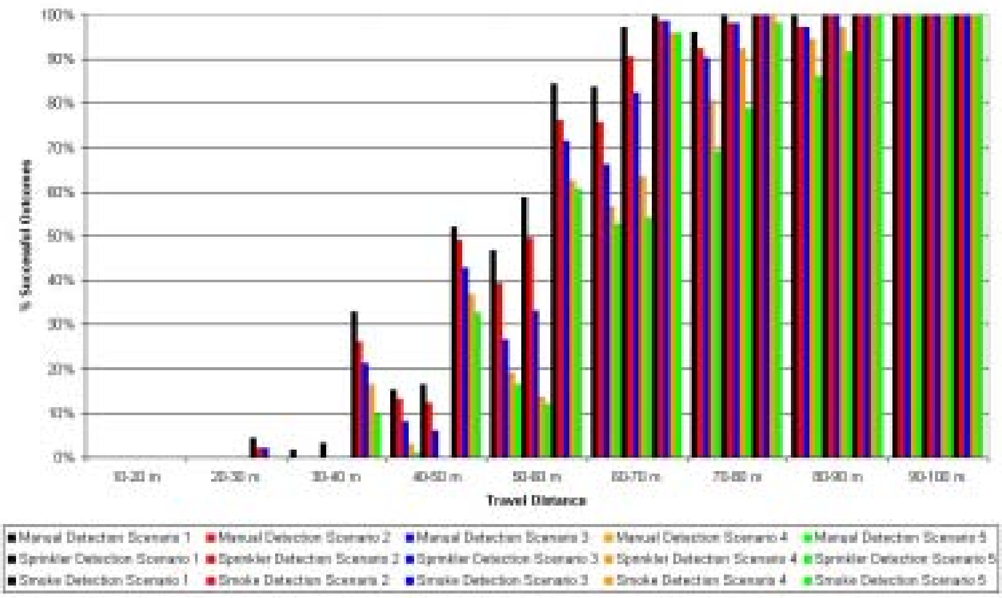

Figure 11.55 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison - Fast Fire Growth Rate

Ultra-Fast Fire Growth Rate

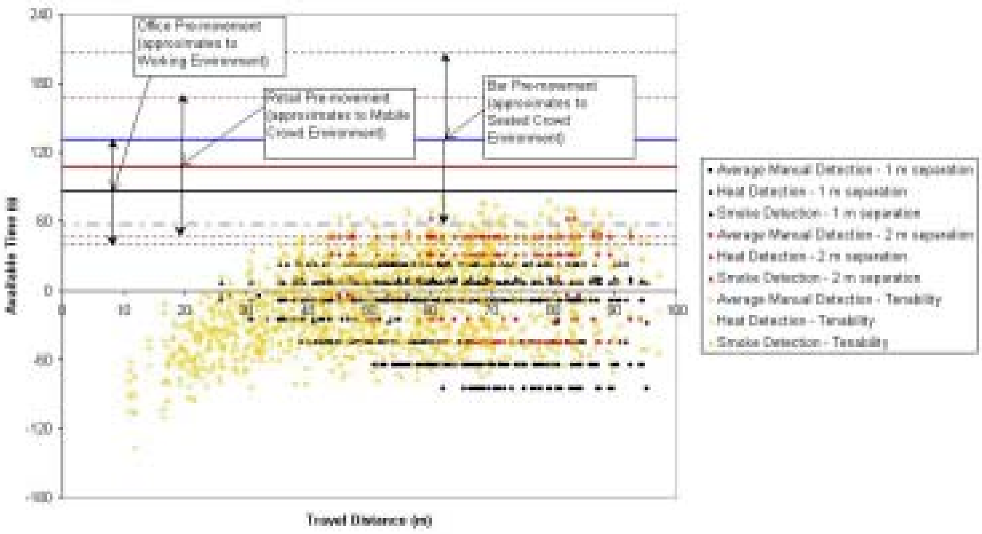

Figure 11.56 : Available Evacuation Time - Ultra-Fast Fire Growth Rate

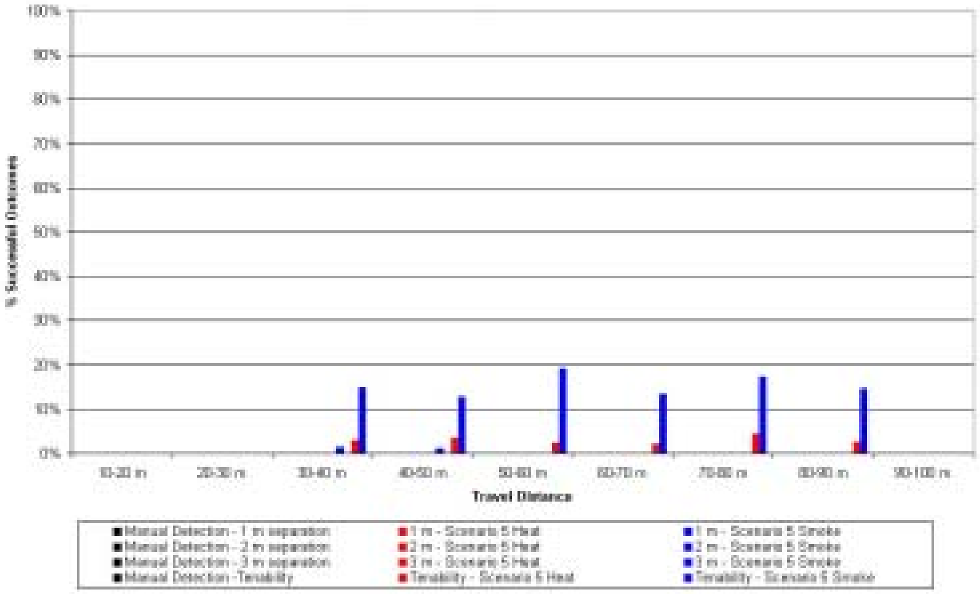

Figure 11.57 : Work Environment Escape Scenario Outcome Comparison - Ultra-Fast Fire Growth Rate

A figure for the Work Environment Escape Manual Detection Scenario Outcome Comparison - Ultra-Fast Fire Growth Rate has not been included as it shows no successful outcomes.

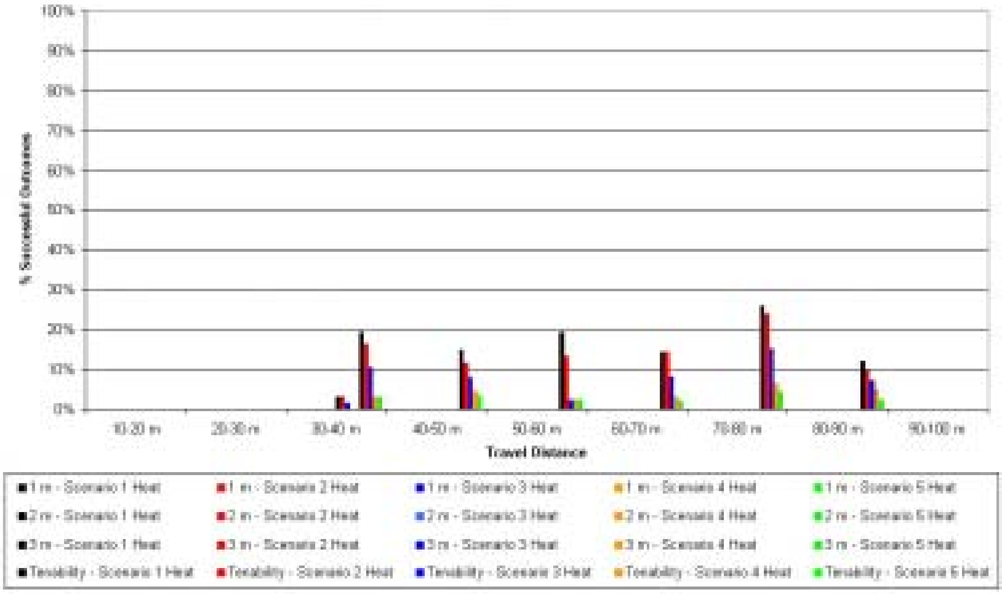

Figure 11.58 : Work Environment Heat Detection Escape Scenario Outcome Comparison - Ultra-Fast Fire Growth Rate

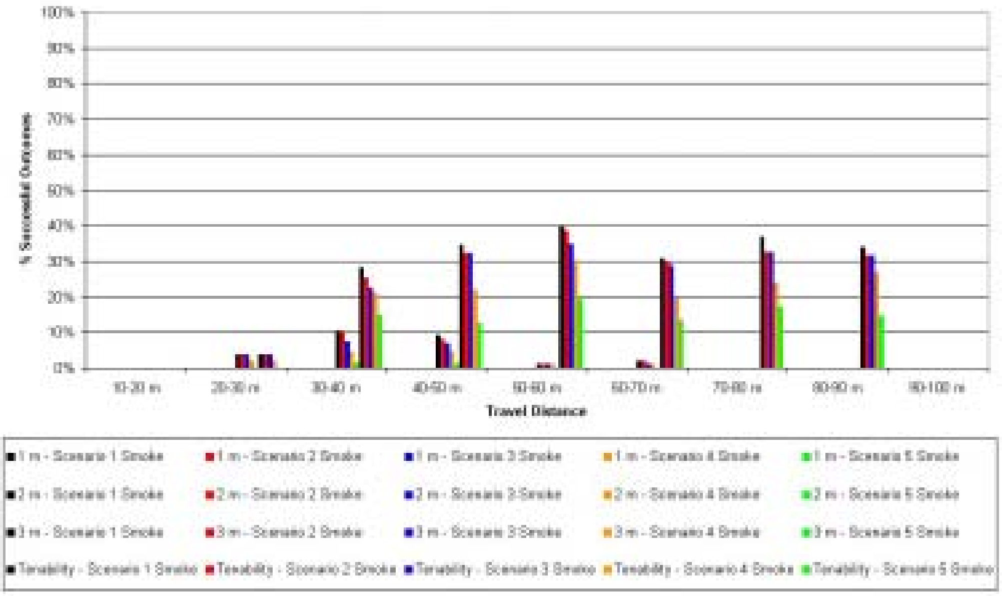

Figure 11.59 : Work Environment Smoke Detection Escape Scenario Outcome Comparison - Ultra-Fast Fire Growth Rate

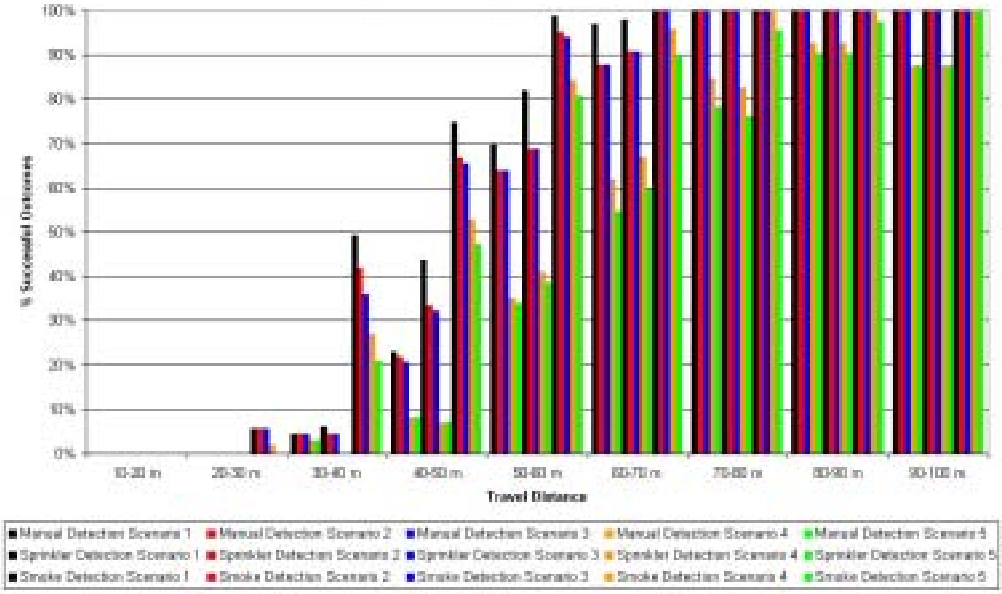

Figure 11.60 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison - Ultra-Fast Fire Growth Rate

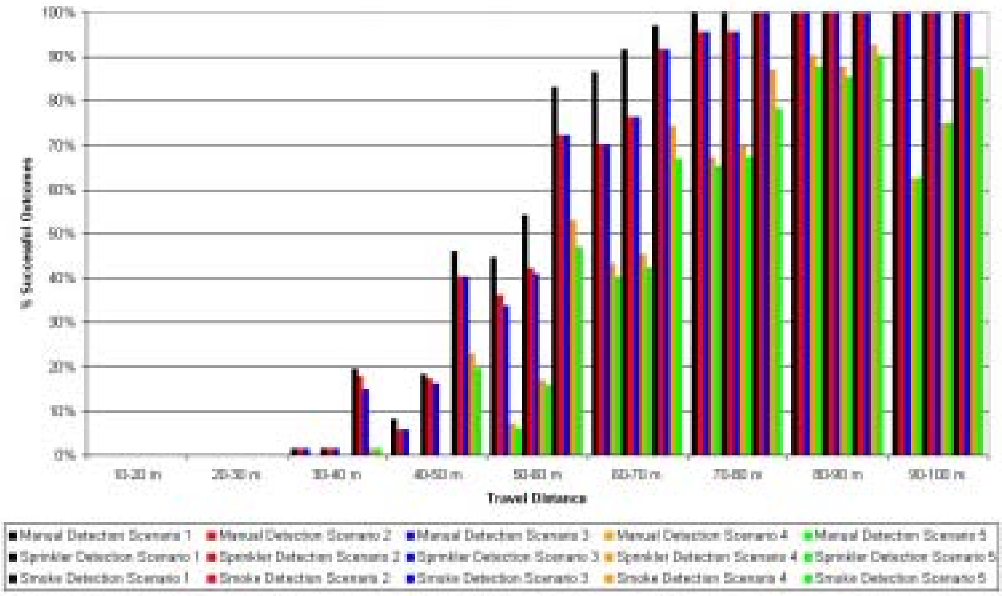

Figure 11.61 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison - Ultra-Fast Fire Growth Rate

12 : GRAPHICAL RESULTS FROM ITEM FIRE ANALYSES

<u>Office Furniture Fires</u>

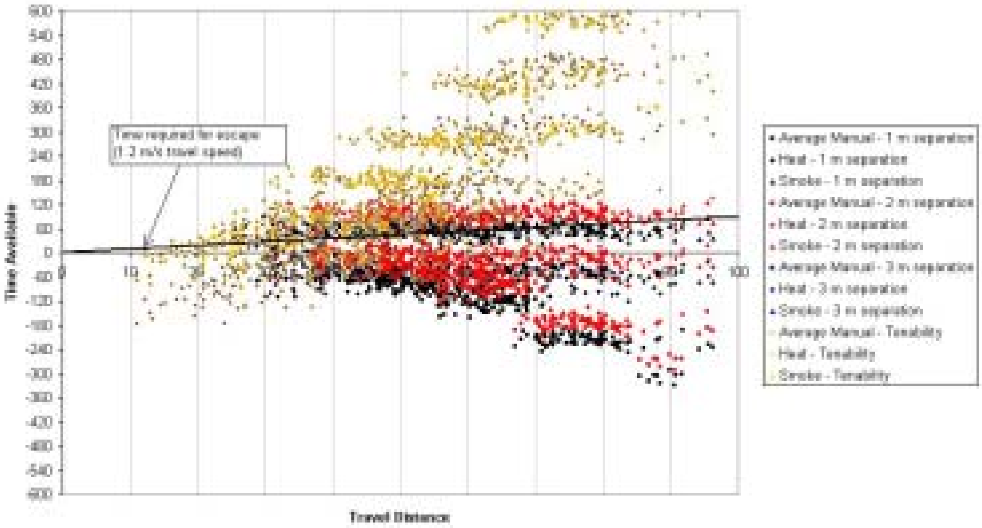

Figure 12.1 : Available Escape Time from 2 Panel Workstation Fire in Work Environment

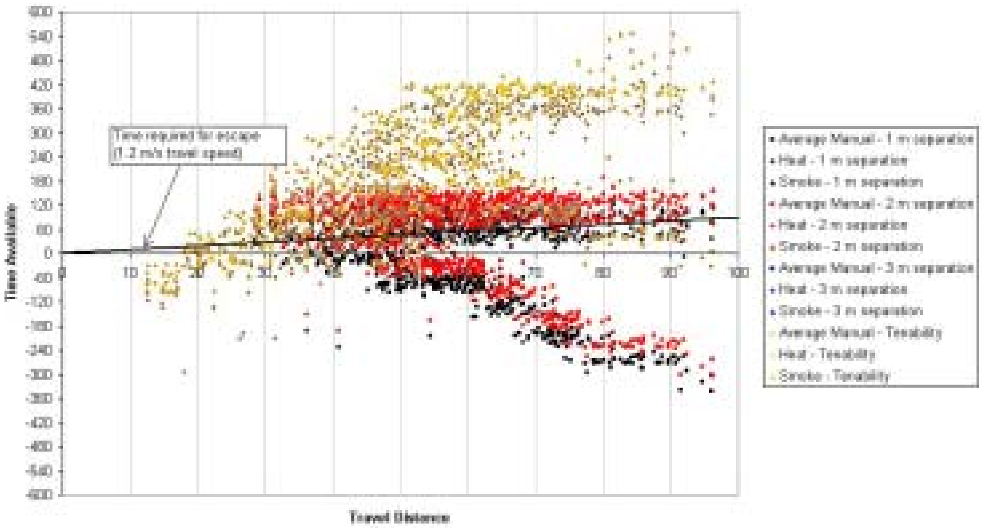

Figure 12.2 : Available Escape Time from 3 Panel Workstation Fire in Work Environment

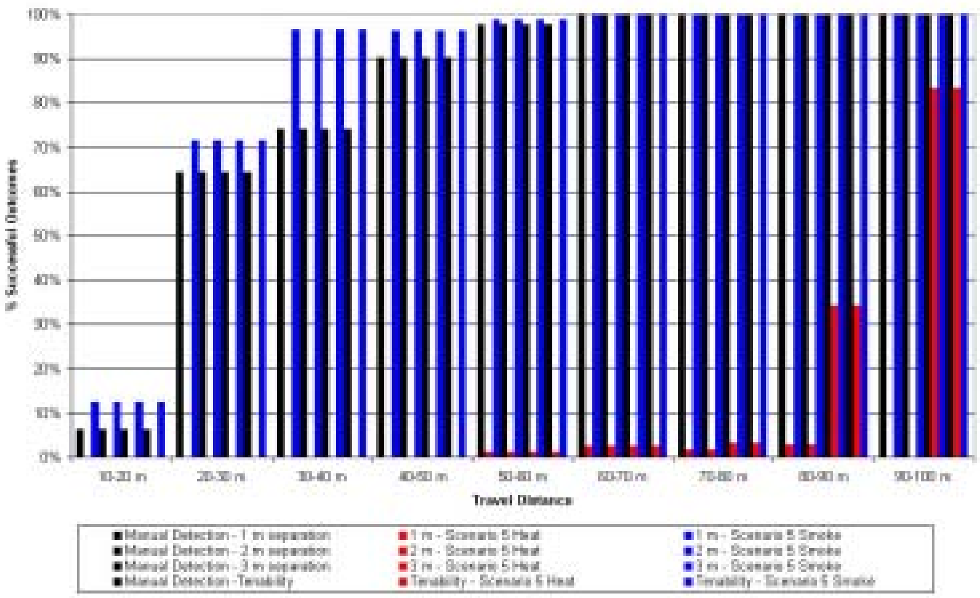

Figure 12.3 : Work Environment Escape Scenario Outcome Comparison – Y0/21 Office Furniture Fire

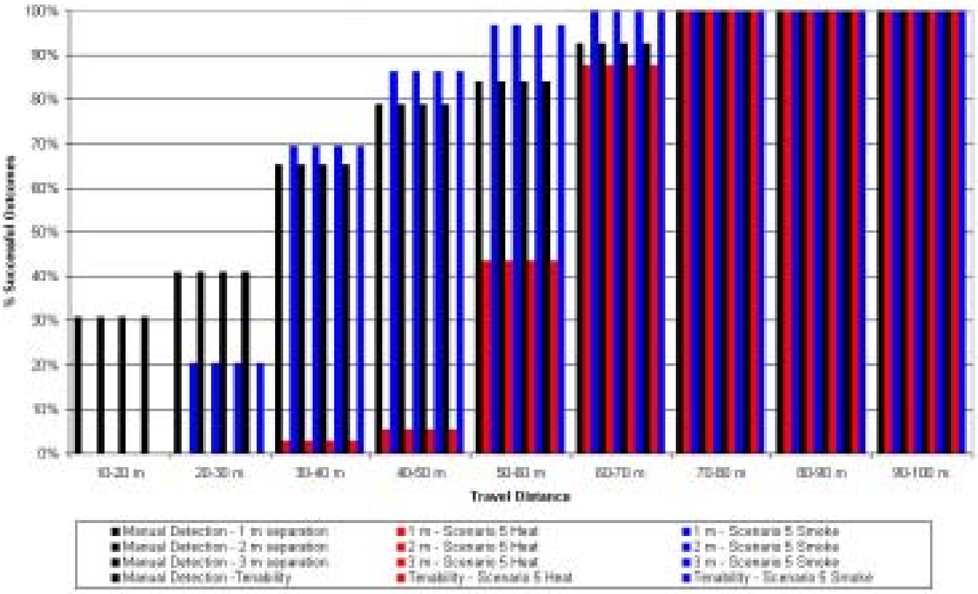

Figure 12.4 : Work Environment Escape Scenario Outcome Comparison – Y0/22 Office Furniture Fire

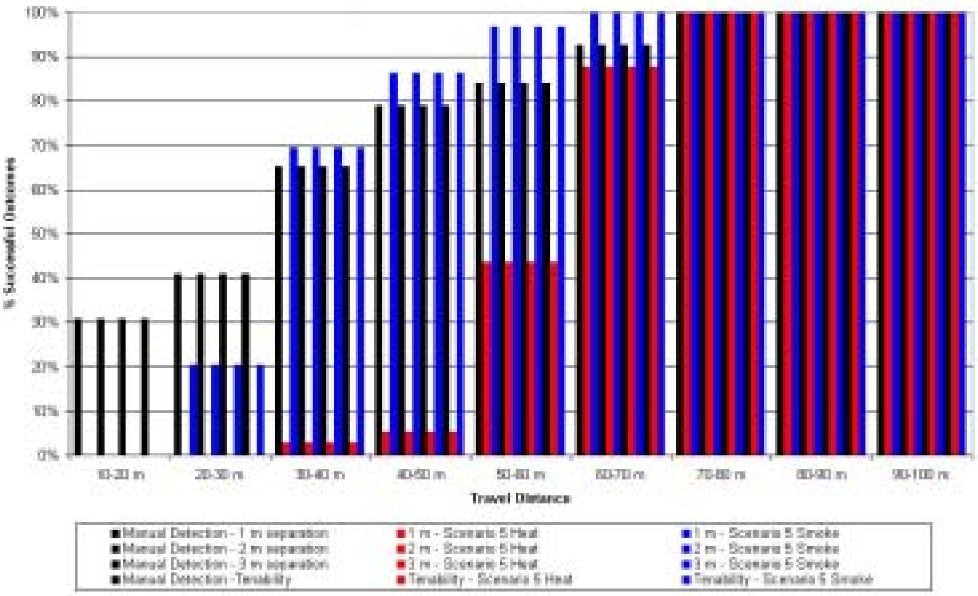

Figure 12.5 : Work Environment Escape Scenario Outcome Comparison – 2 Panel Workstation Fire

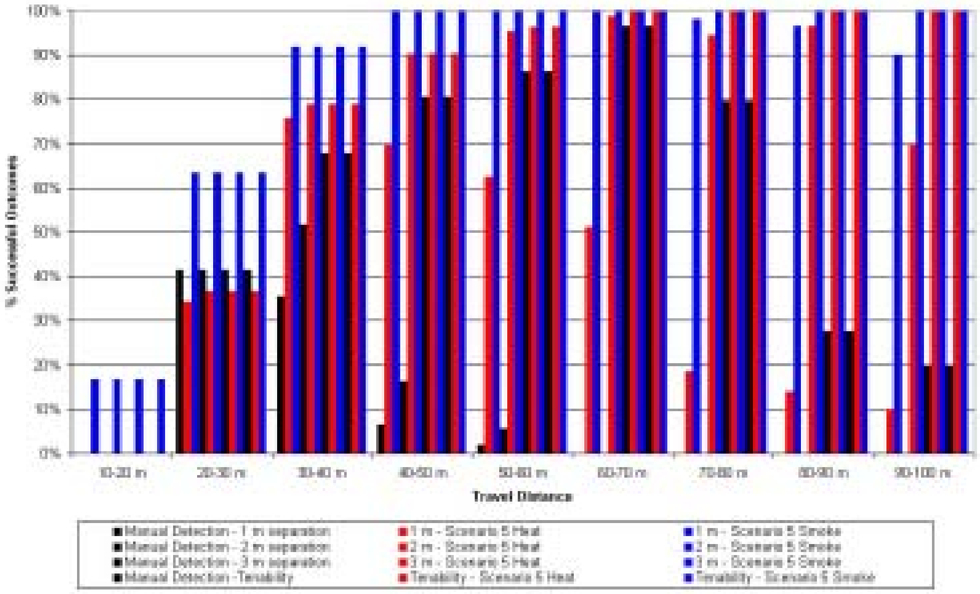

Figure 12.6 : Work Environment Escape Scenario Outcome Comparison – 3 Panel Workstation Fire

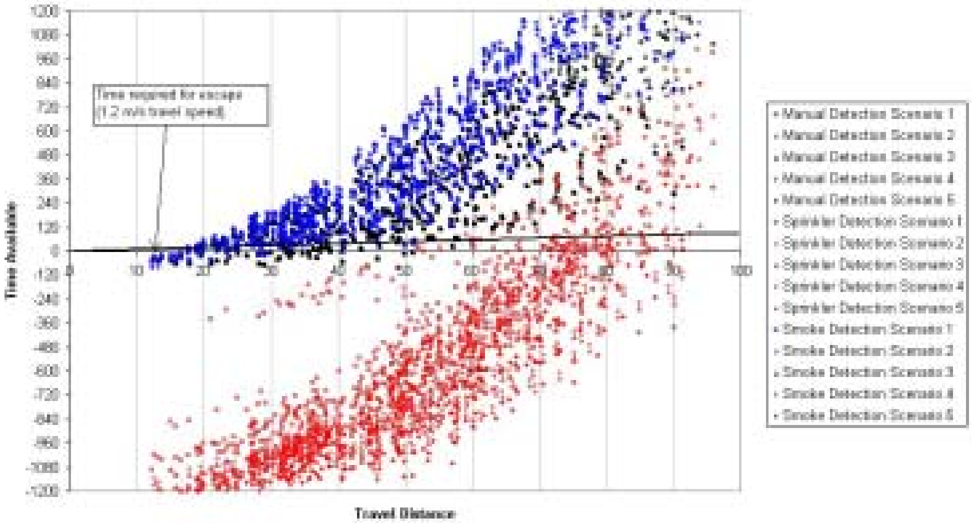

Figure 12.7 : Available Escape Time from Sprinkler Protected Work Environment – Y0/21 Office Furniture Fire

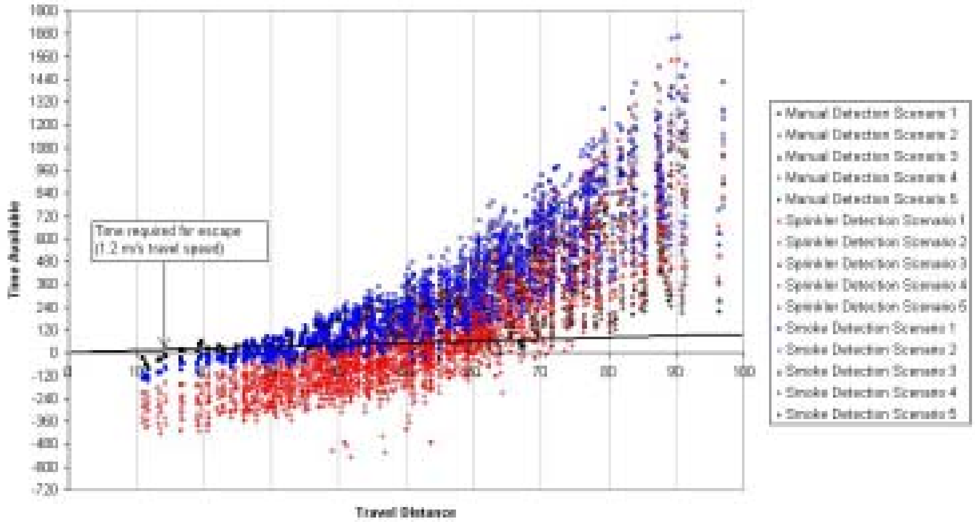

Figure 12.8 : Available Escape Time from Sprinkler Protected Work Environment – Y0/22 Office Furniture Fire

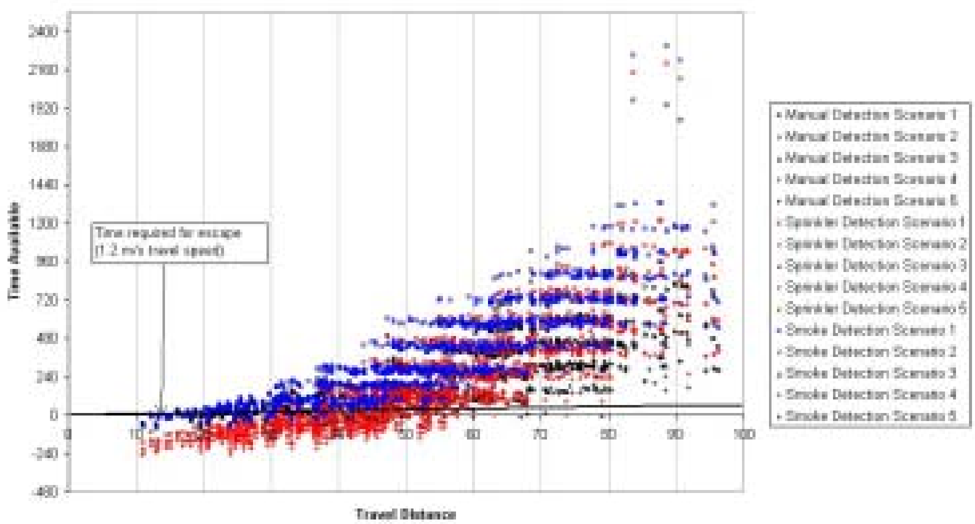

Figure 12.9 : Available Escape Time from Sprinkler Protected Work Environment – 2 Panel Workstation Fire

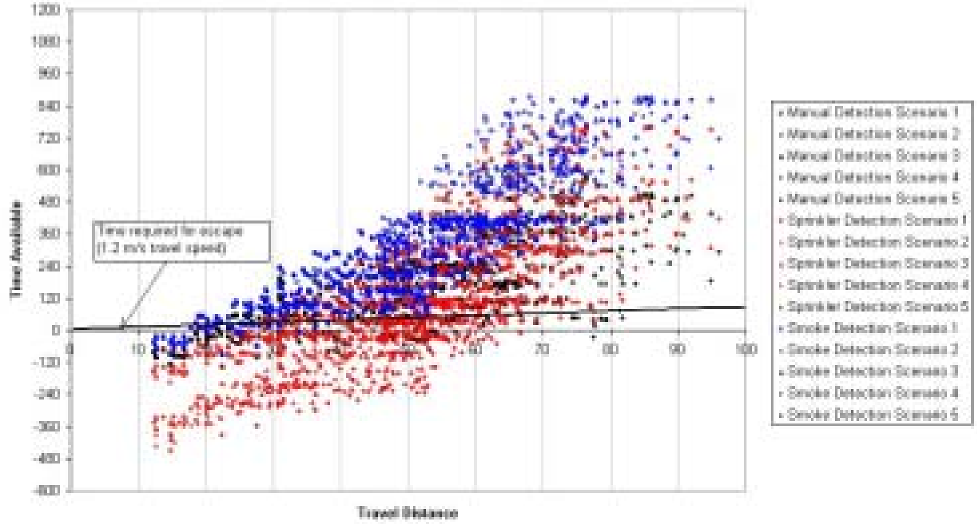

Figure 12.10 : Available Escape Time from Sprinkler Protected Work Environment – 3 Panel Workstation Fire

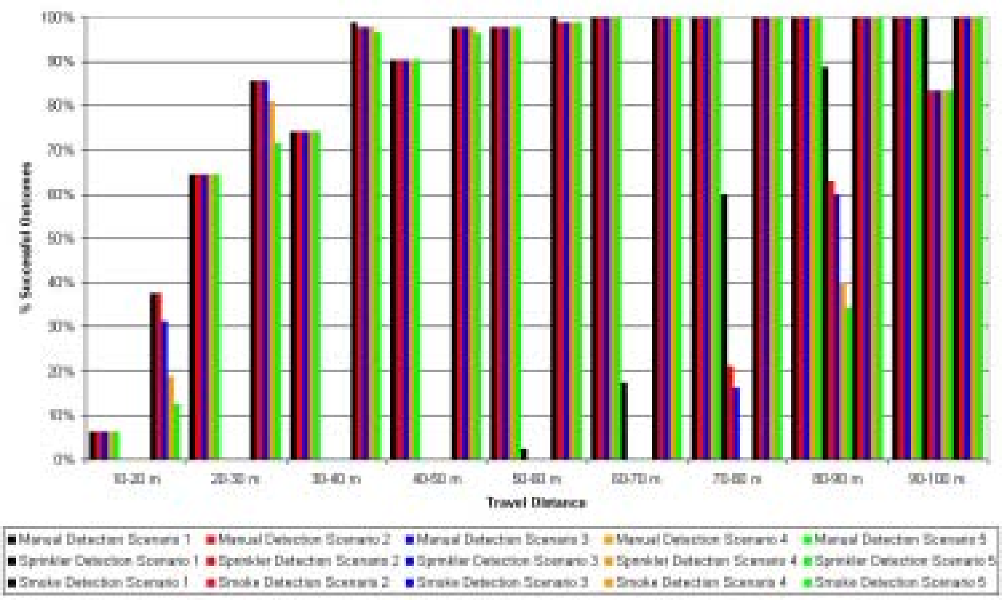

Figure 12.11 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y0/21 Office Furniture Fire

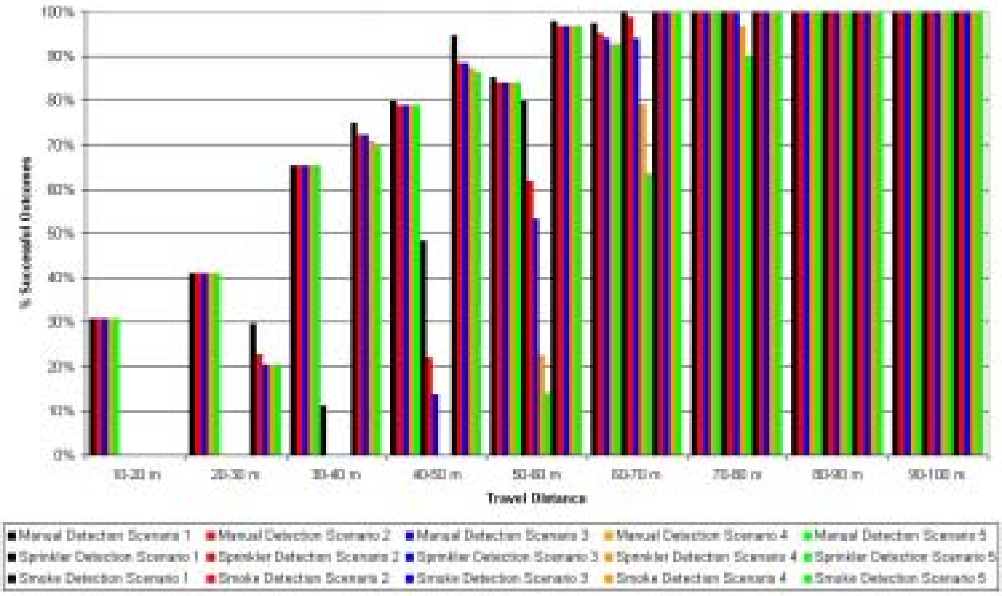

Figure 12.12 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y0/22 Office Furniture Fire

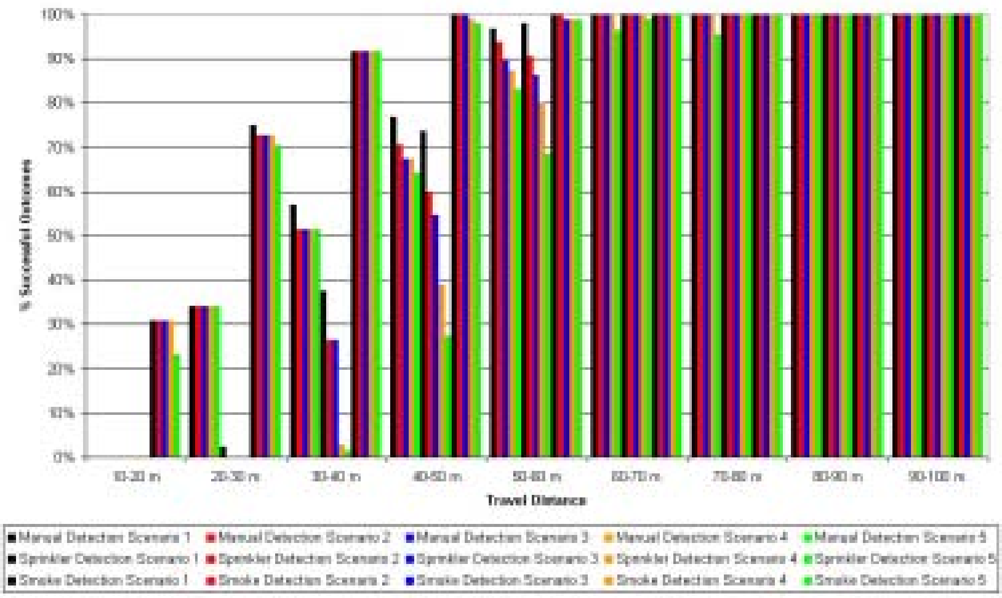

Figure 12.13 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison - 2 Panel Workstation Fire

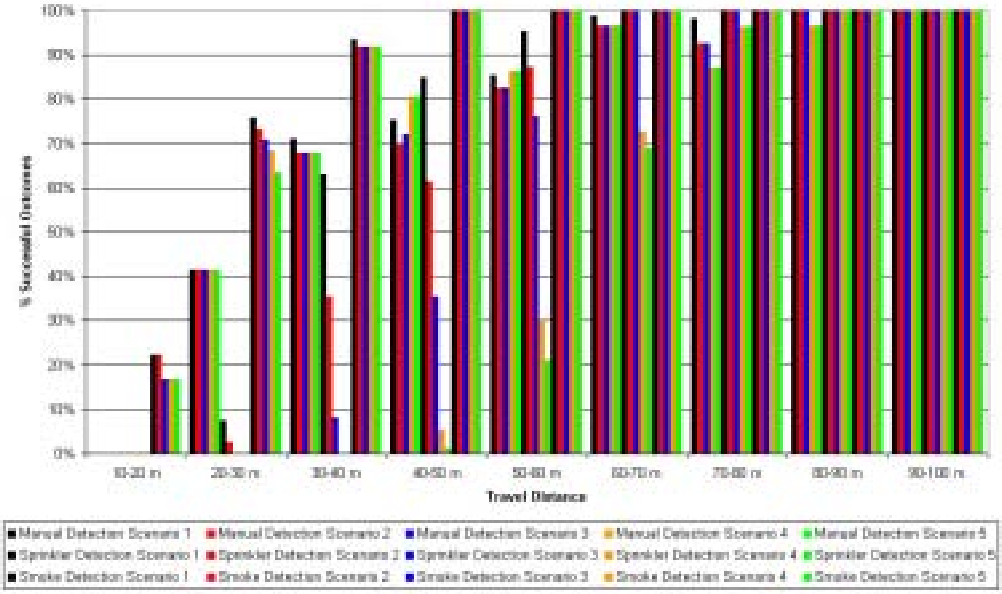

Figure 12.14 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – 3 Panel Workstation Fire

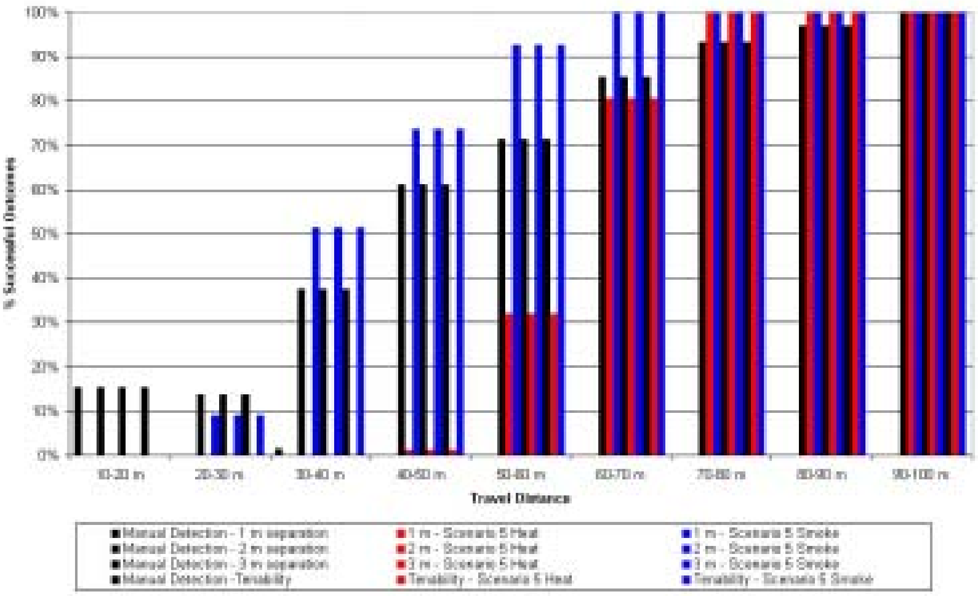

Figure 12.15 : Mobile Crowd Environment Escape Scenario Outcome Comparison - Y0/22 Office Furniture Fire

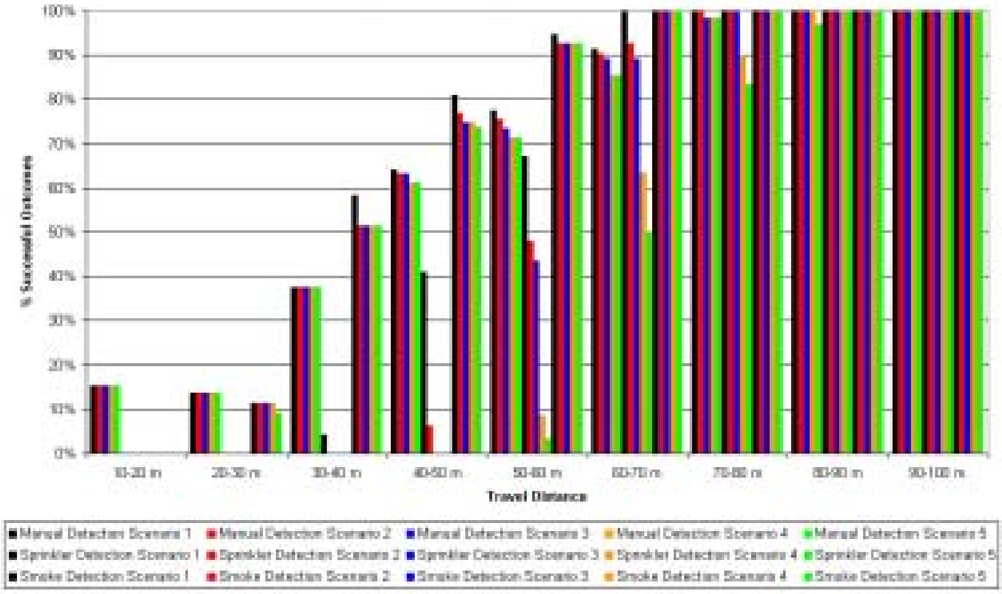

Figure 12.16 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison - Y0/22 Office Furniture Fire

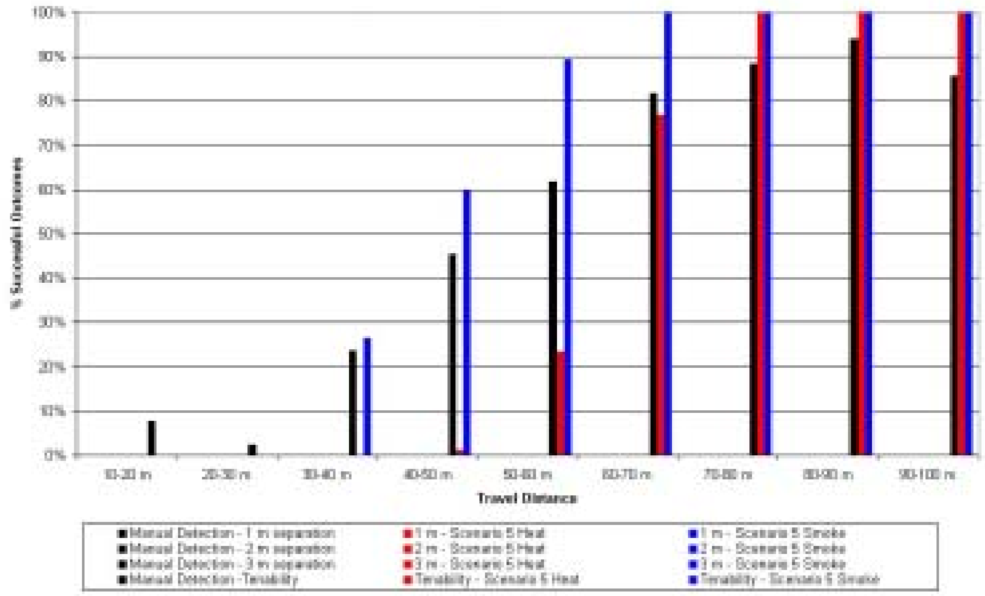

Figure 12.17 : Seated Crowd Environment Escape Scenario Outcome Comparison - Y0/22 Office Furniture Fire

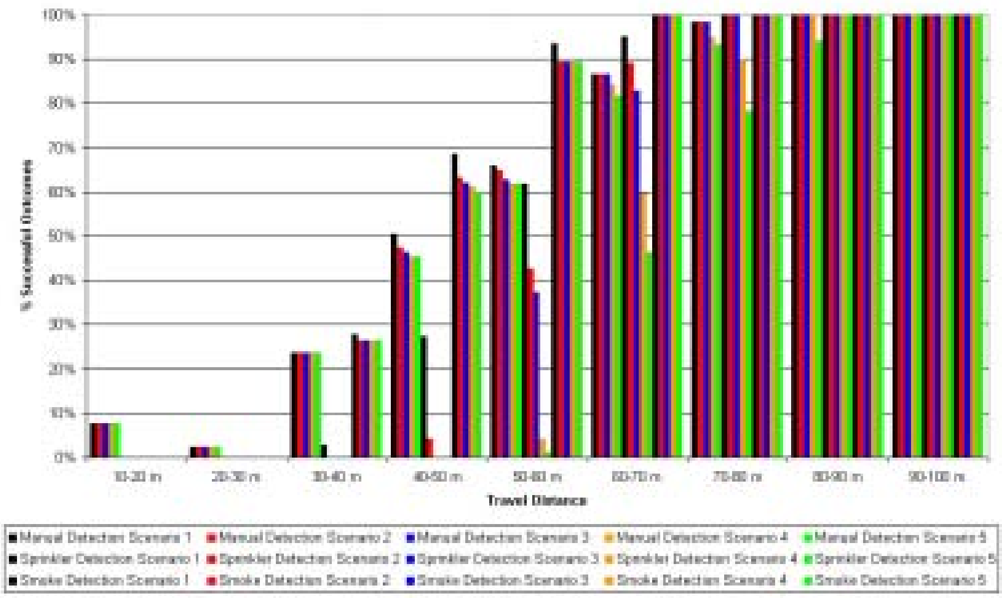

Figure 12.18 : Seated Crowd Environment Sprinkler Protection Escape Scenario Comparison - Y0/22 Office Fire

<u>Soft Furnishing Fires</u>

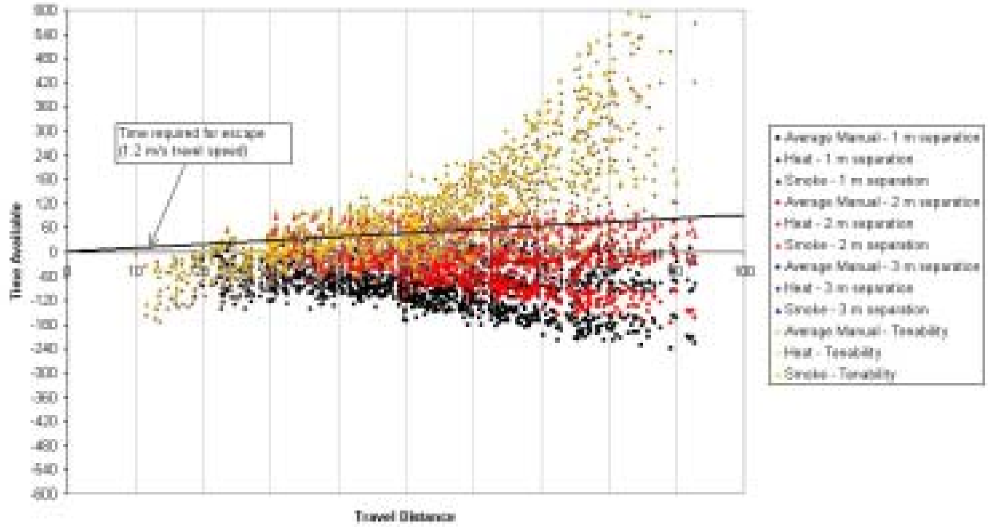

Figure 12.19 : Available Escape Time from Work Environment – Y5.0/14 Stackable Chair Fire

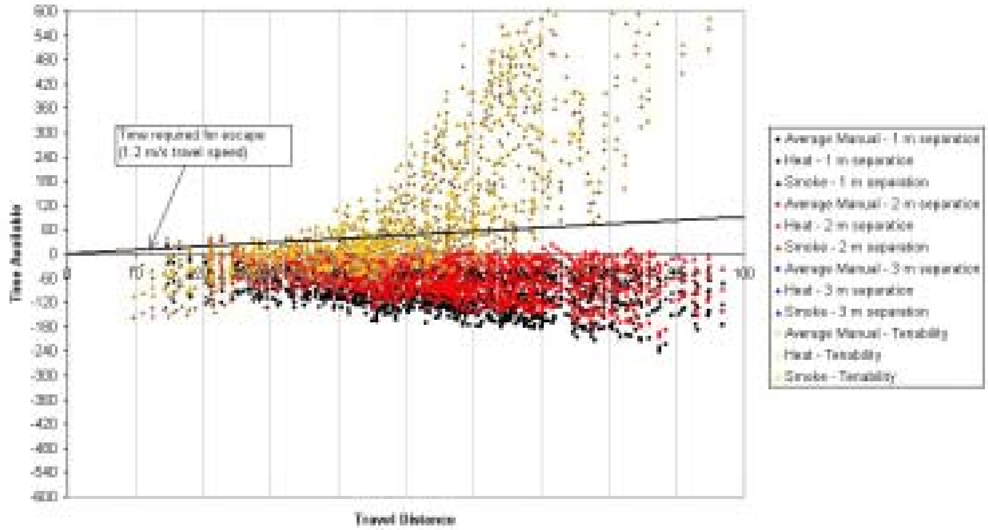

Figure 12.20 : Available Escape Time from Work Environment – Y5.3/10 Chair Fire

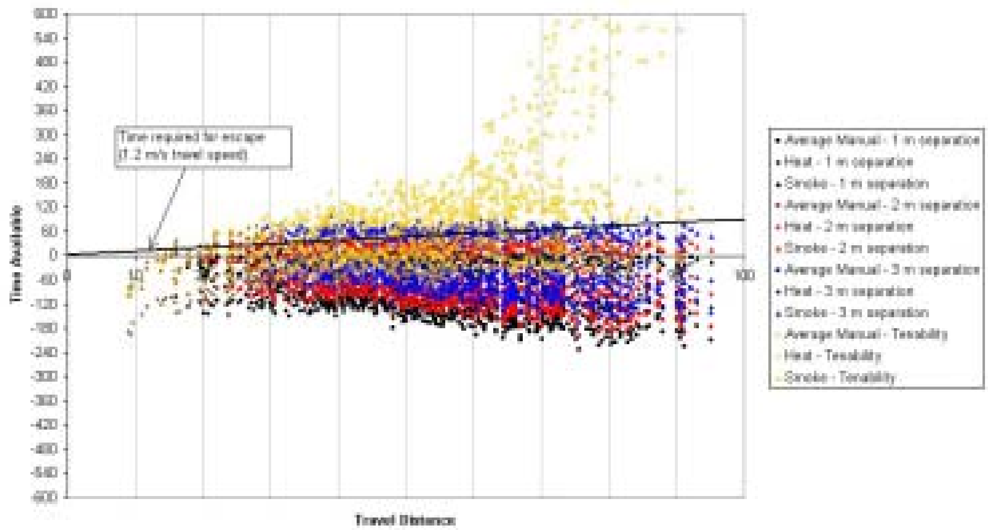

Figure 12.21 : Available Escape Time from Work Environment – Y5.4/21 Sofa Fire

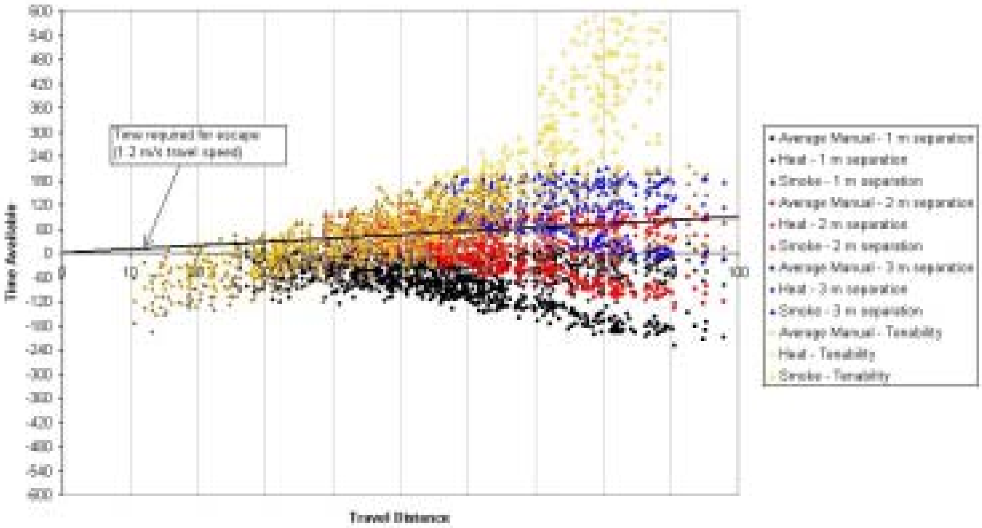

Figure 12.22 : Available Escape Time from Work Environment – Loveseat Fire

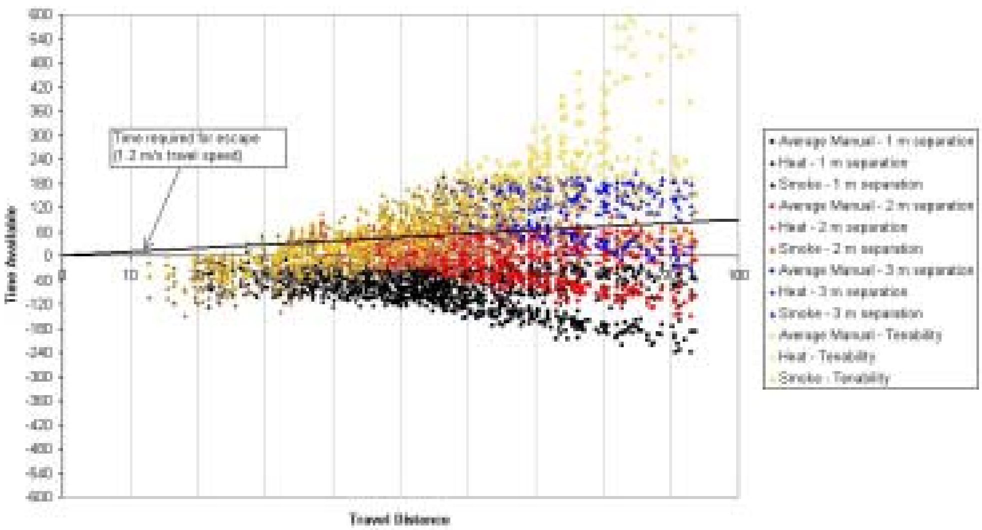

Figure 12.23 : Available Escape Time from Work Environment – Sofa Fire

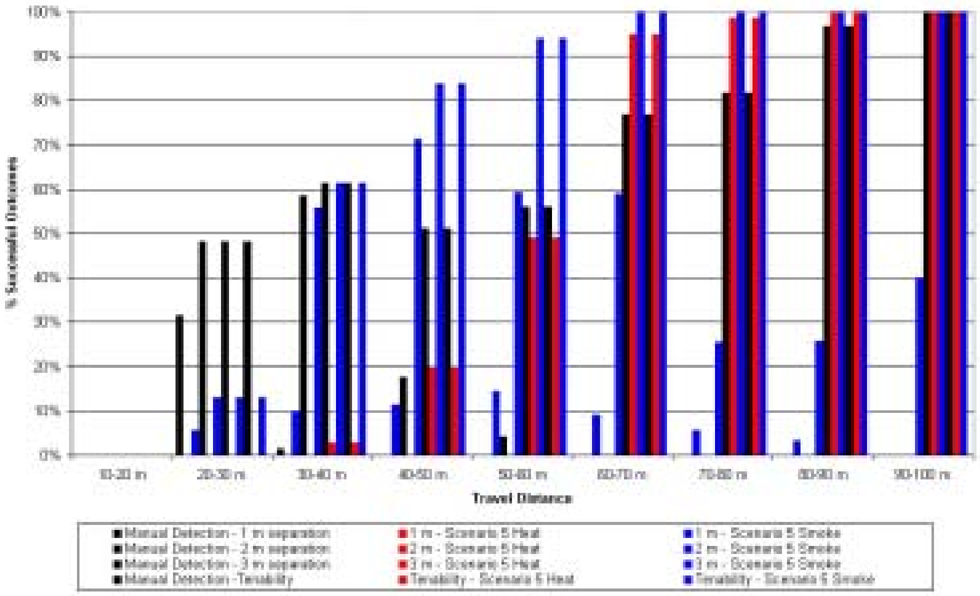

Figure 12.24 : Work Environment Escape Scenario Outcome Comparison – Y5.0/14 Stackable Chair Fire

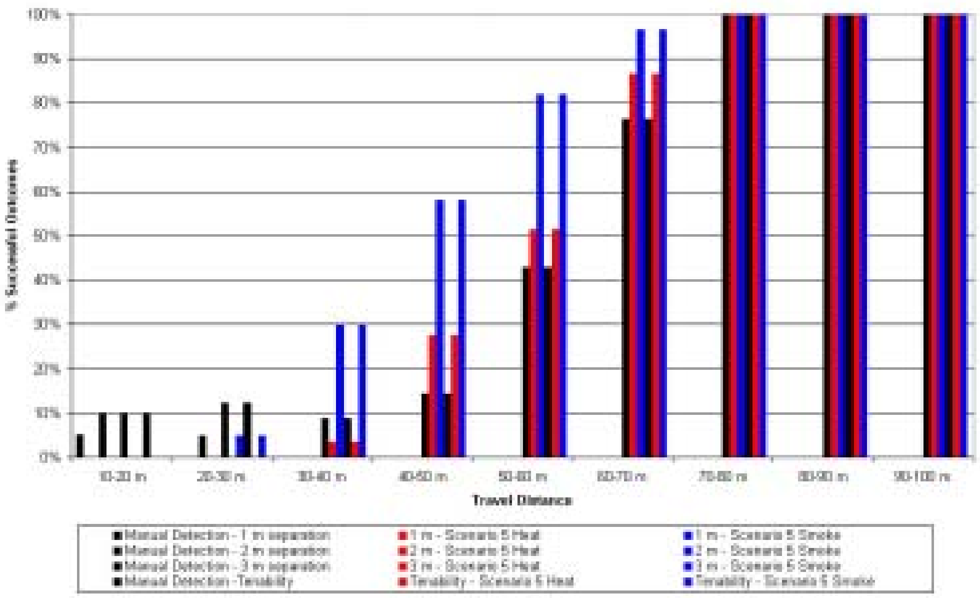

Figure 12.25 : Work Environment Escape Scenario Outcome Comparison – Y5.3/10 Chair Fire

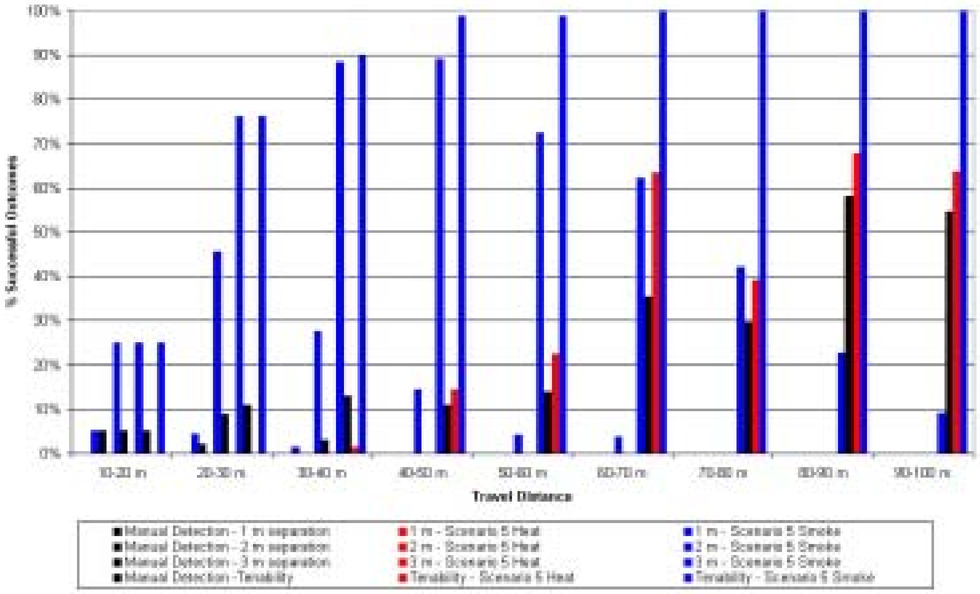

Figure 12.26 : Work Environment Escape Scenario Outcome Comparison – Y5.4/21 Sofa Fire

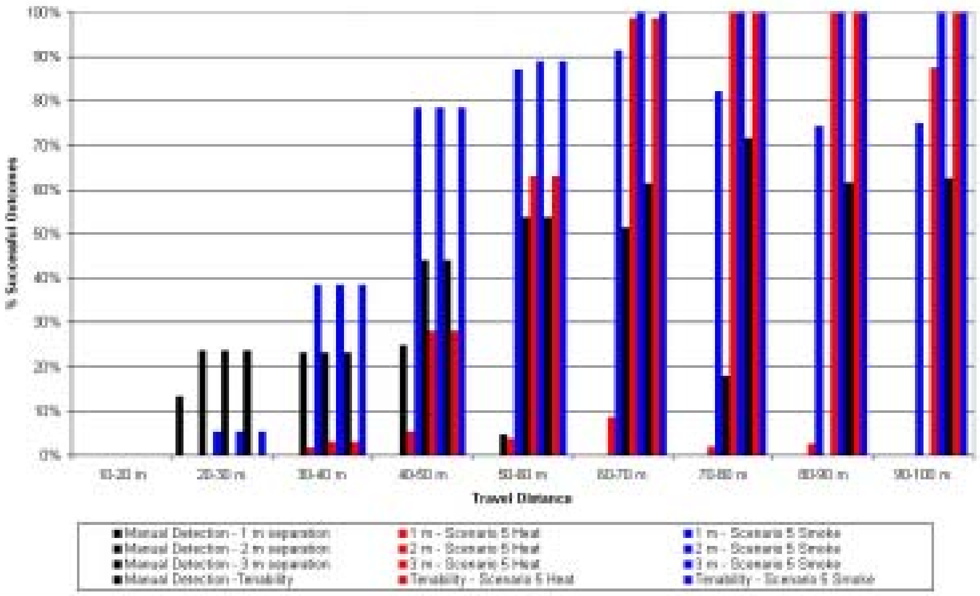

Figure 12.27 : Work Environment Escape Scenario Outcome Comparison – Loveseat Fire

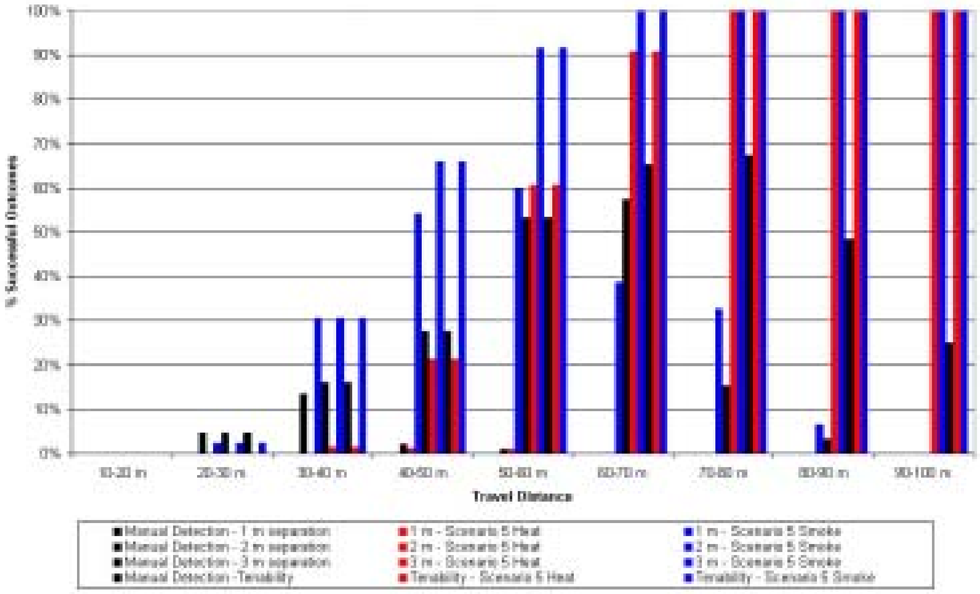

Figure 12.28 : Work Environment Escape Scenario Outcome Comparison – Sofa Fire

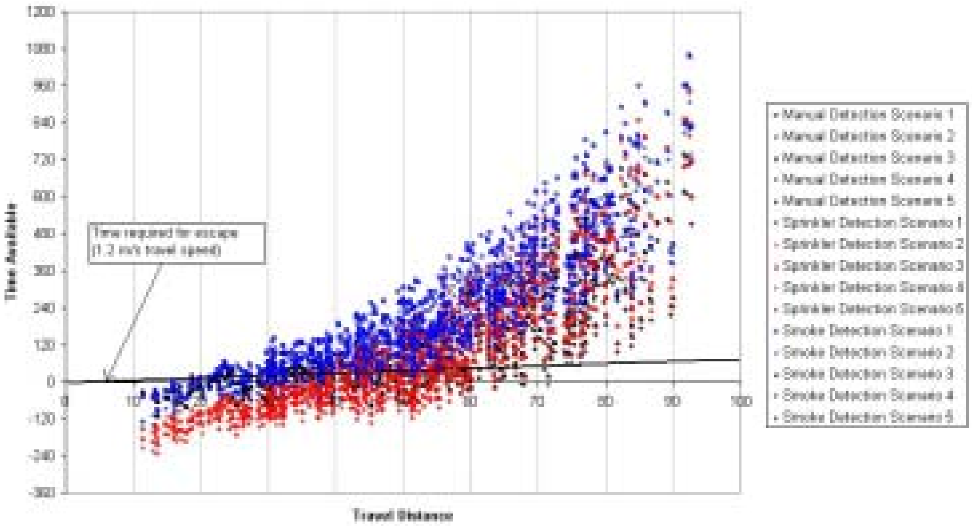

Figure 12.29 : Available Escape Time from Sprinkler Protected Work Environment – Y5.0/14 Stackable Chair Fire

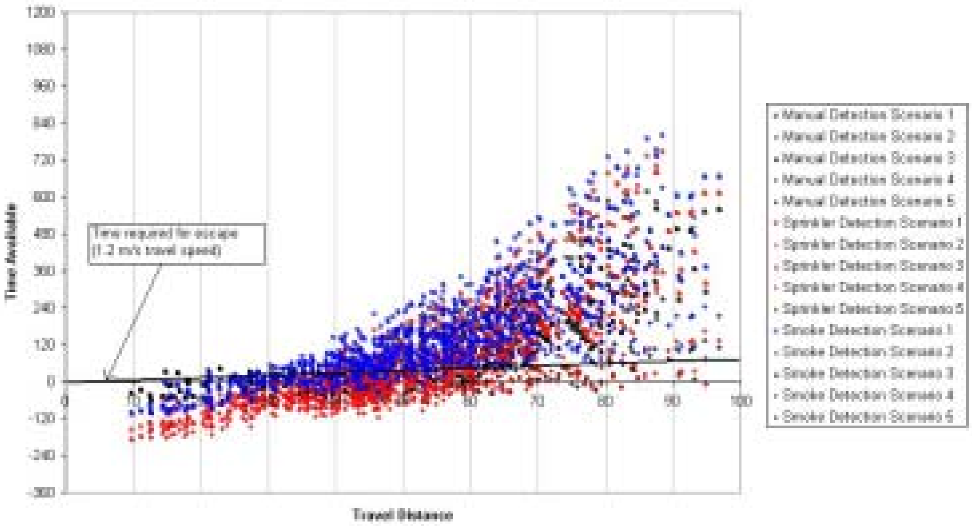

Figure 12.30 : Available Escape Time from Sprinkler Protected Work Environment – Y5.3/10 Chair Fire

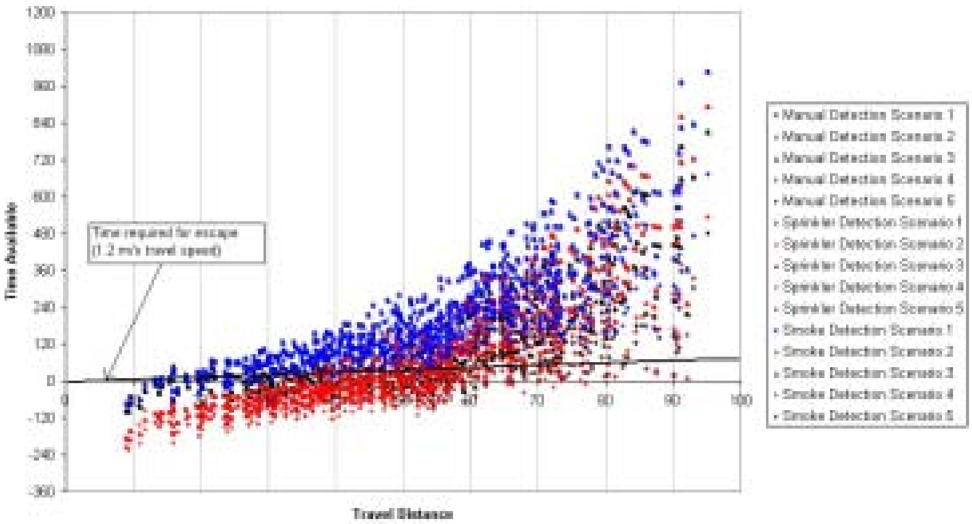

Figure 12.31 : Available Escape Time from Sprinkler Protected Work Environment – Y5.4/21 Sofa Fire

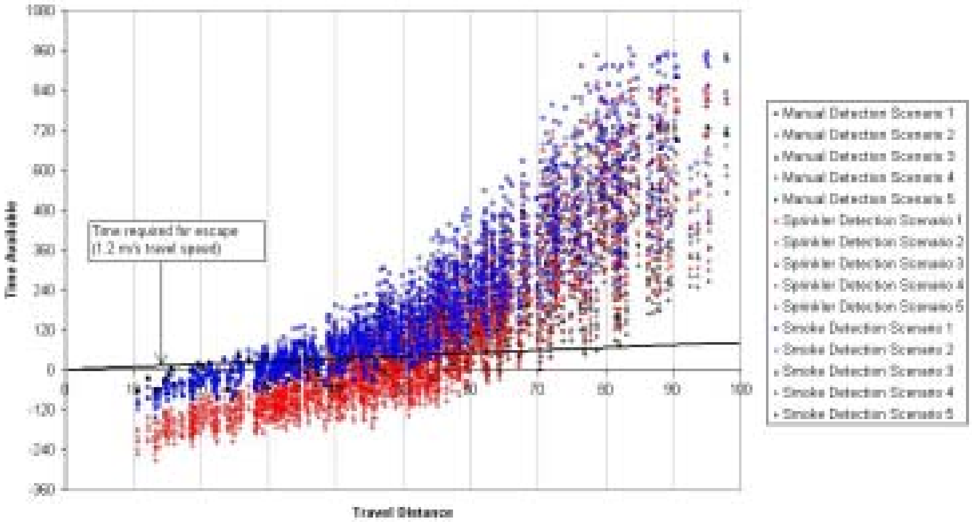

Figure 12.32 : Available Escape Time from Sprinkler Protected Work Environment – Loveseat Fire

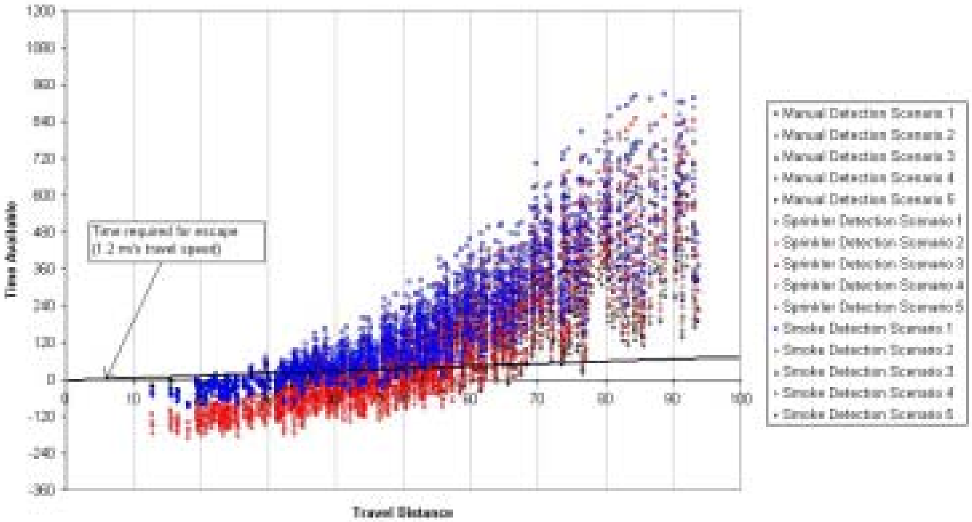

Figure 12.33 : Available Escape Time from Sprinkler Protected Work Environment – Sofa Fire

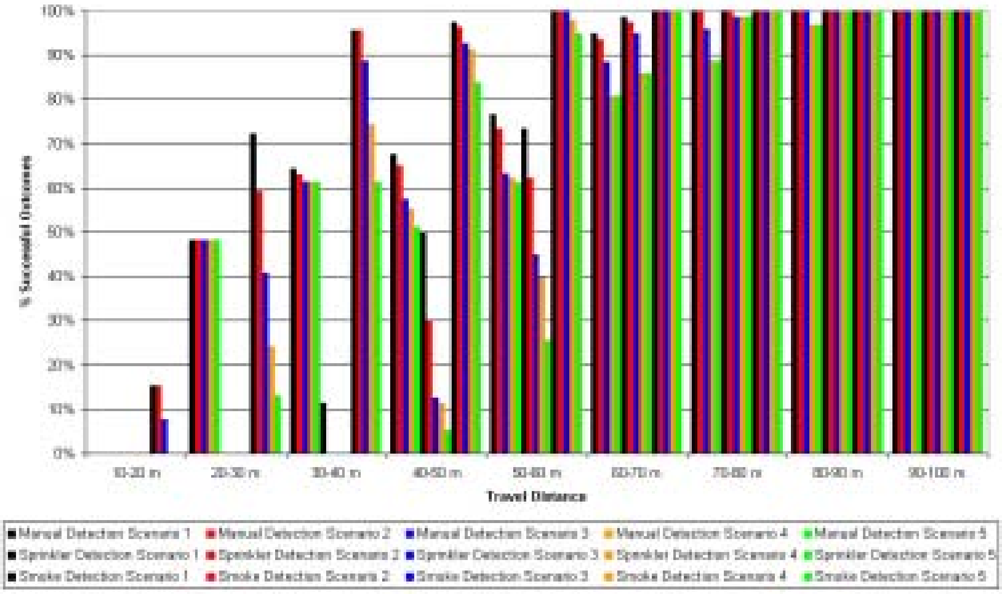

Figure 12.34 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y5.0/14 Stackable Chair Fire

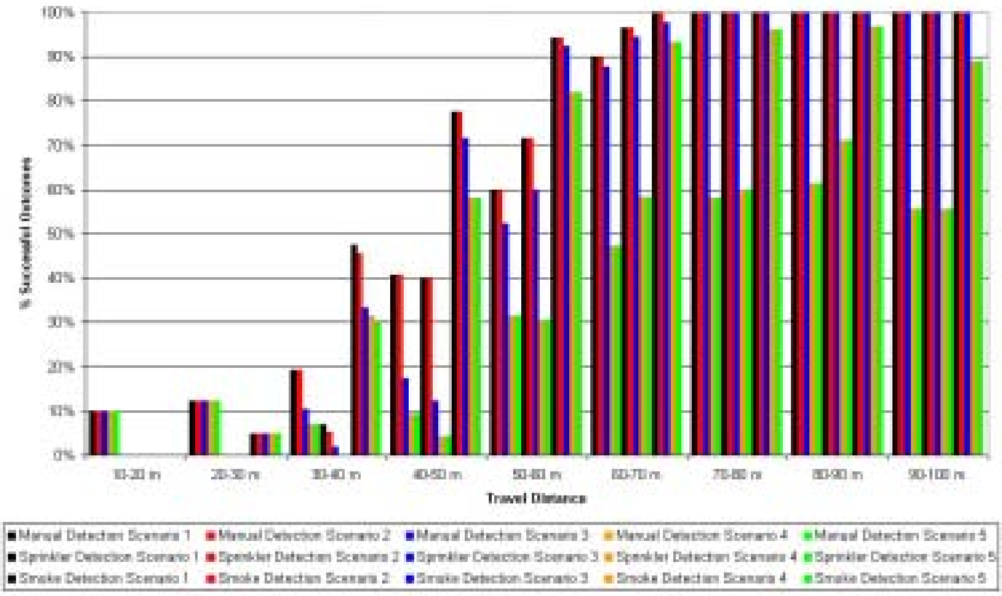

Figure 12.35 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y5.3/10 Chair Fire

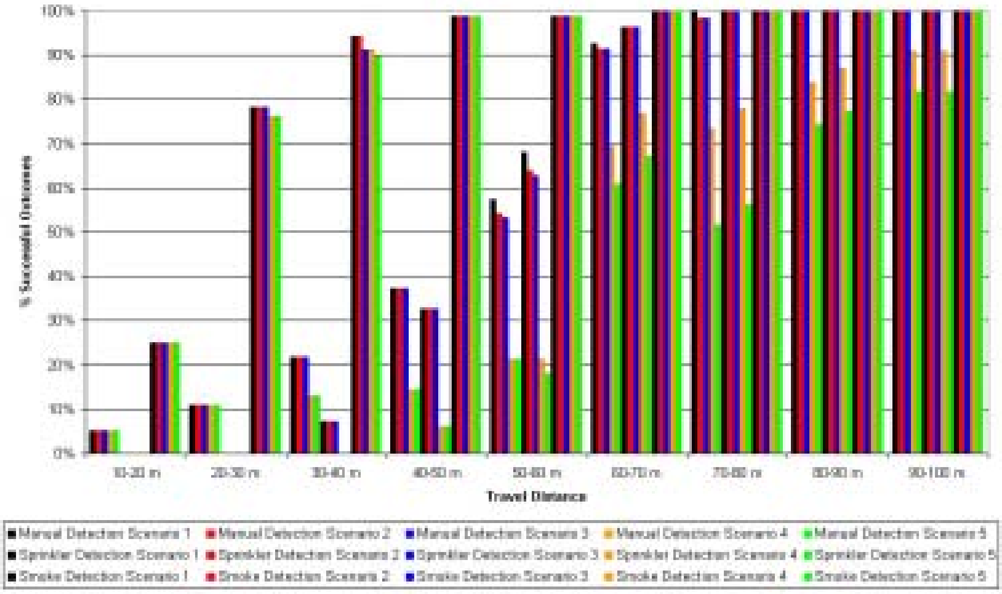

Figure 12.36 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y5.4/21 Sofa Fire

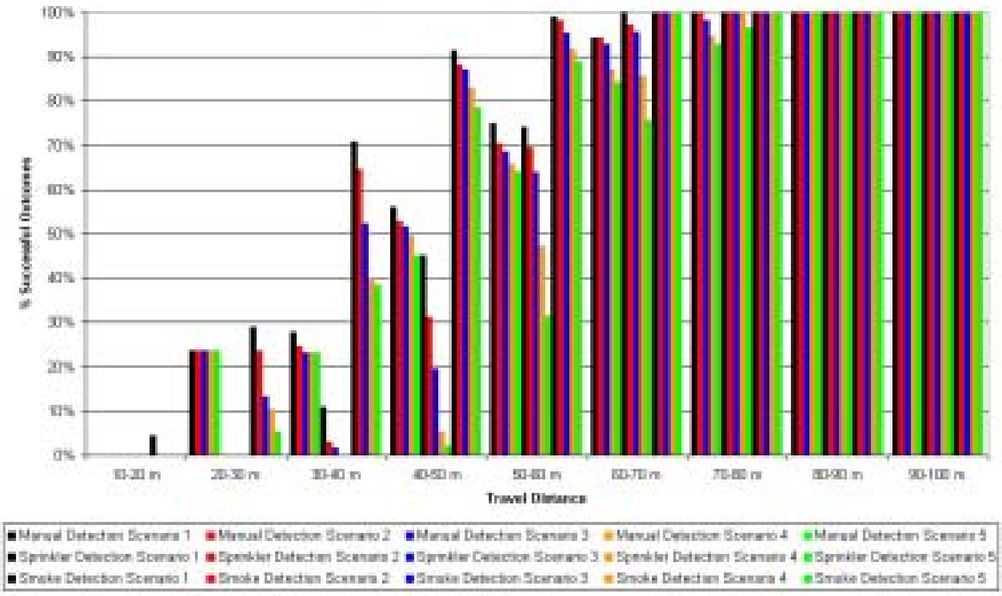

Figure 12.37 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Loveseat Fire

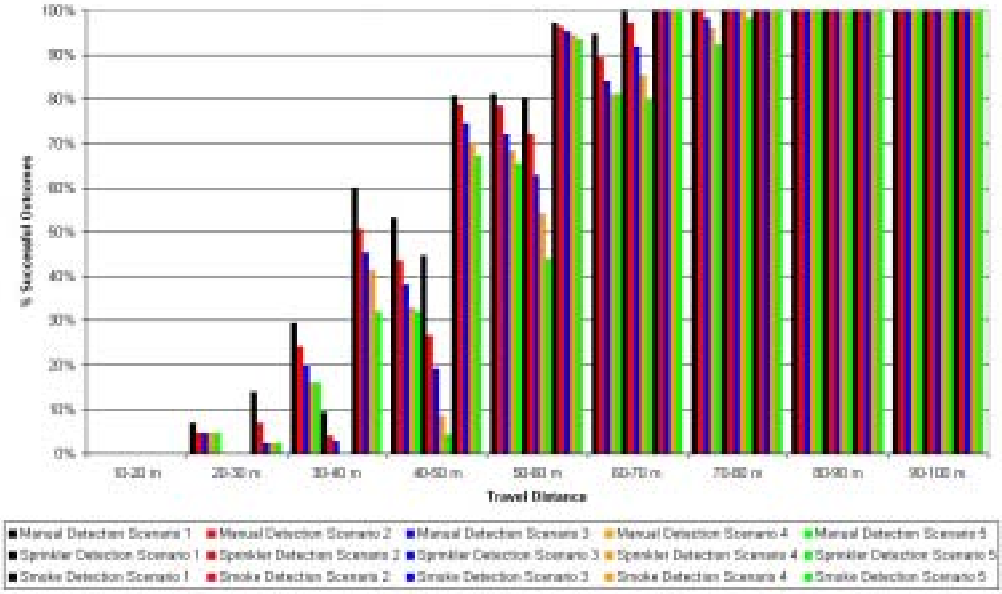

Figure 12.38 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Sofa Fire

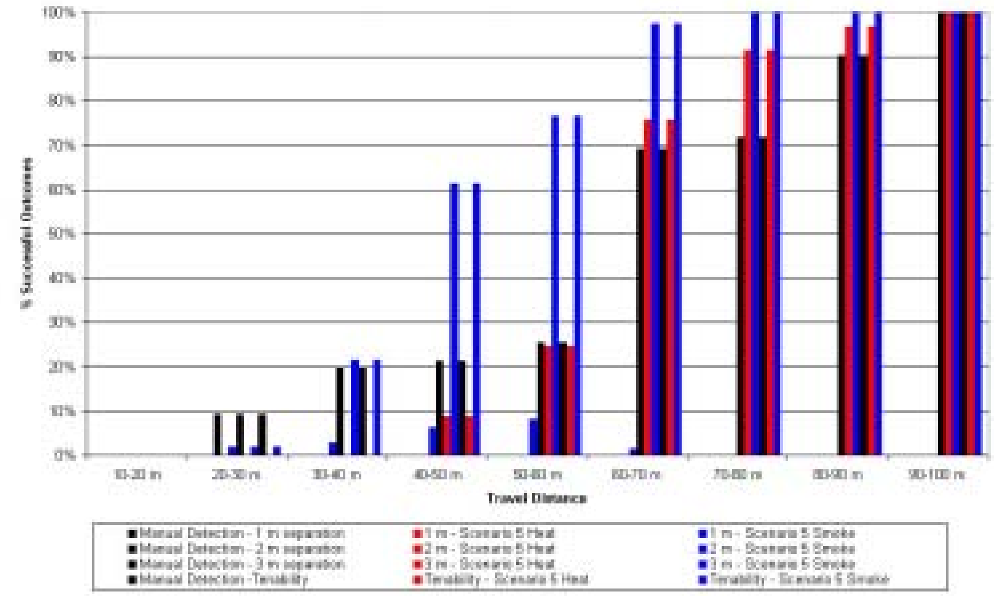

Figure 12.39 : Mobile Crowd Environment Escape Scenario Outcome Comparison – Y5.0/14 Stackable Chair Fire

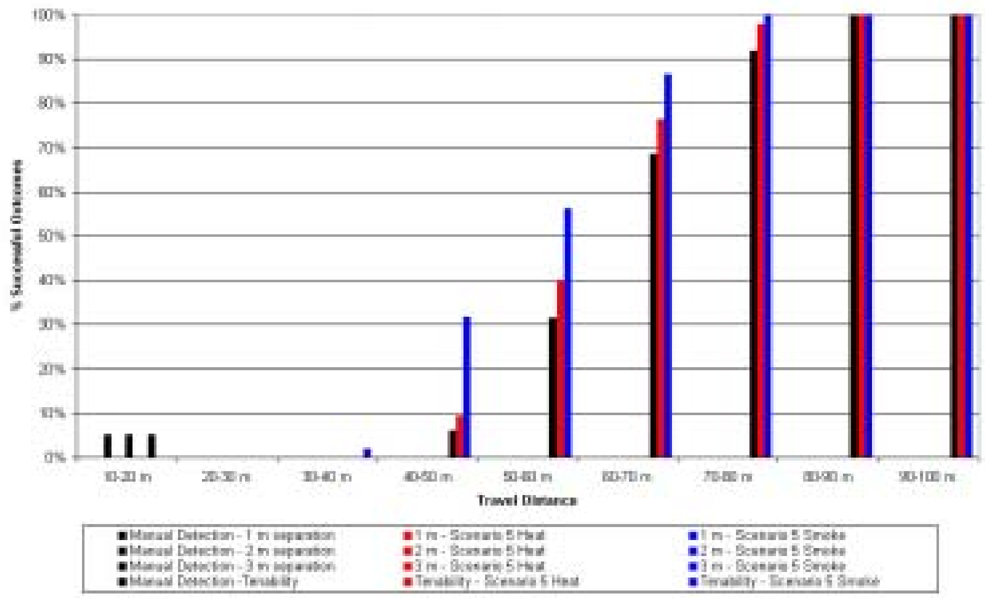

Figure 12.40 : Mobile Crowd Environment Escape Scenario Outcome Comparison – Y5.3/10 Chair Fire

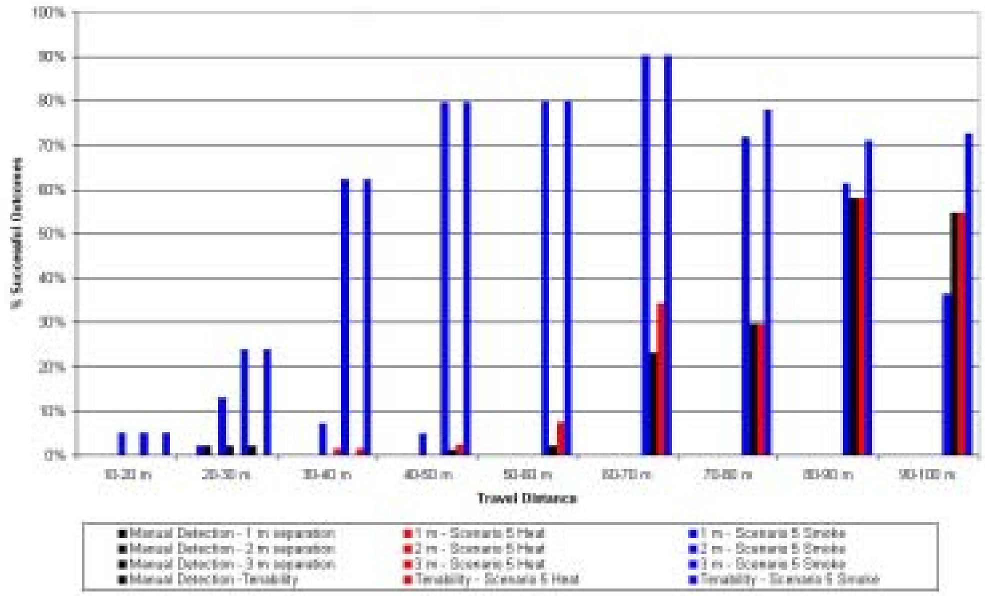

Figure 12.41 : Mobile Crowd Environment Escape Scenario Outcome Comparison – Y5.4/21 Sofa Fire

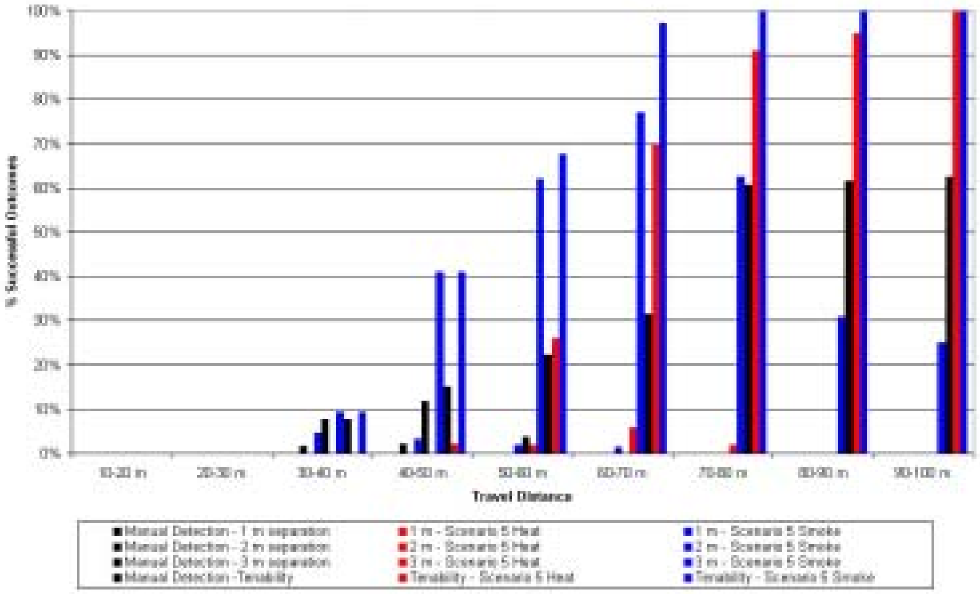

Figure 12.42 : Mobile Crowd Environment Escape Scenario Outcome Comparison – Loveseat Fire

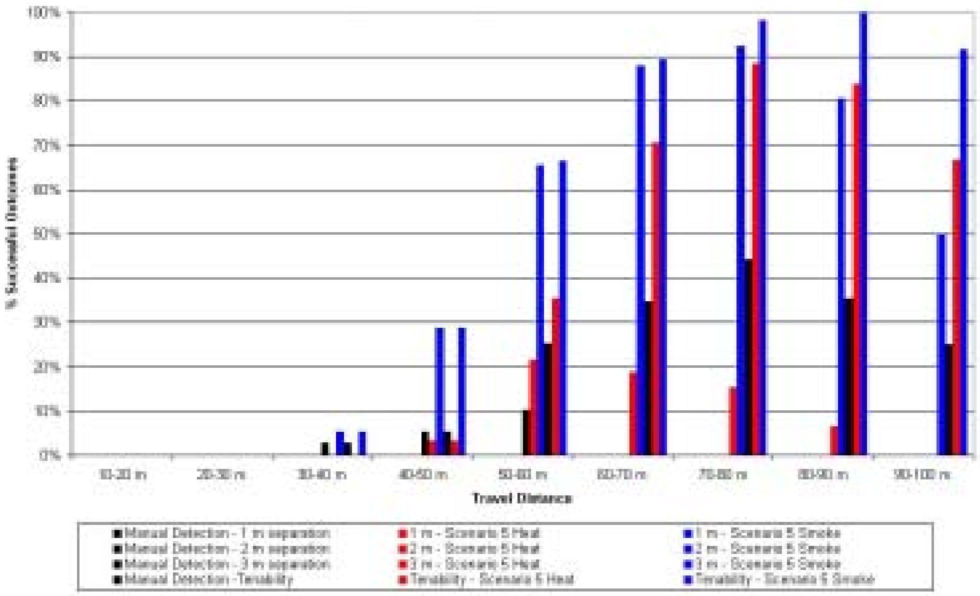

Figure 12.43 : Mobile Crowd Environment Escape Scenario Outcome Comparison – Sofa Fire

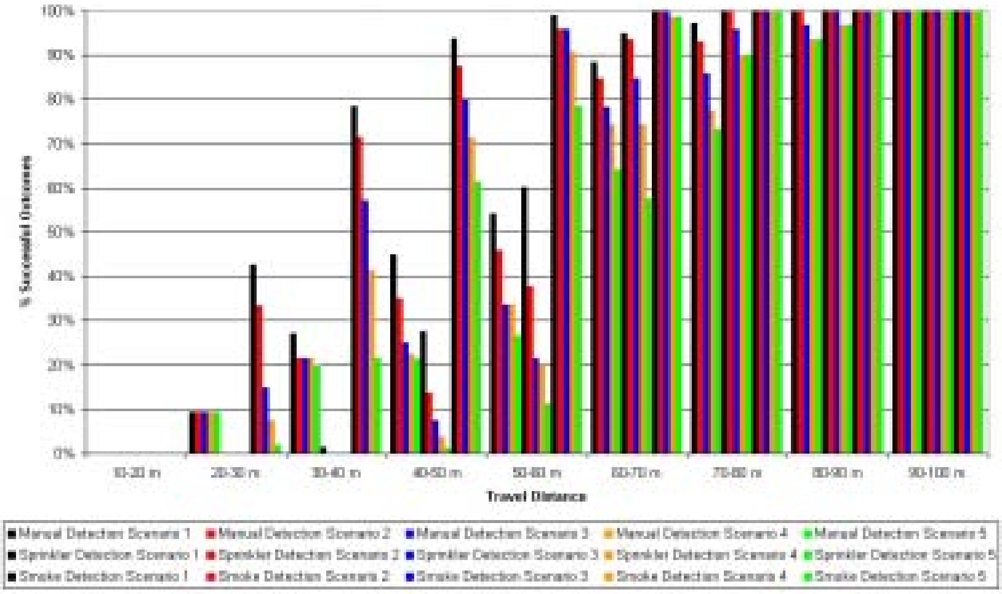

Figure 12.44 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y5.0/14 Stackable Chair Fire

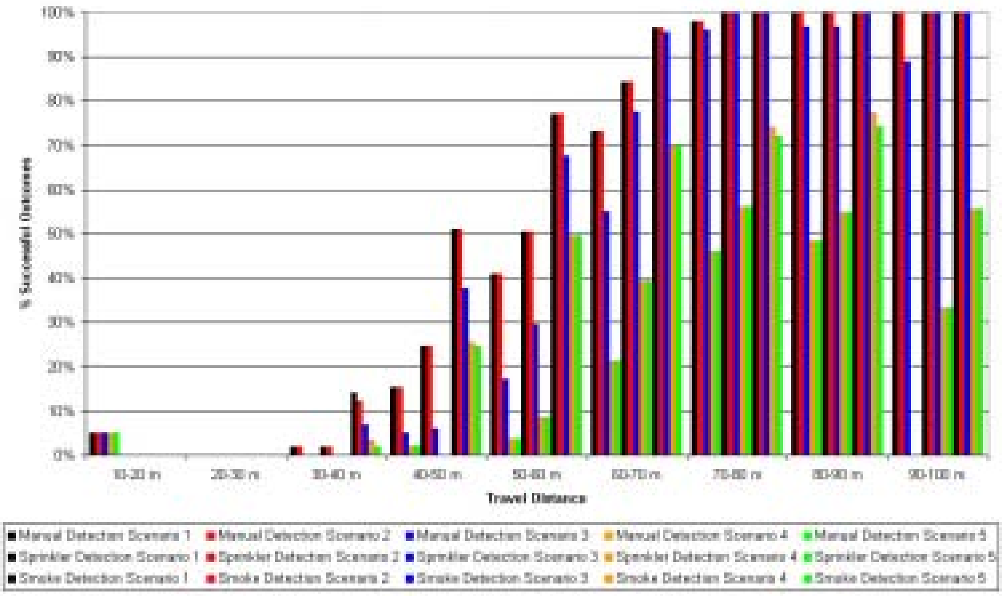

Figure 12.45 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y5.3/10 Chair Fire

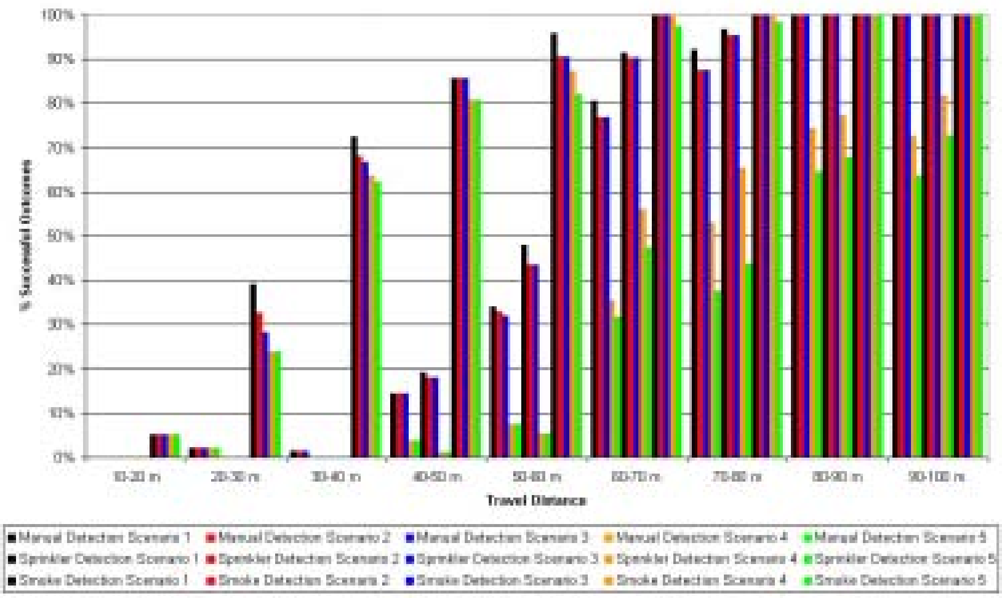

Figure 12.46 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y5.4/21 Sofa Fire

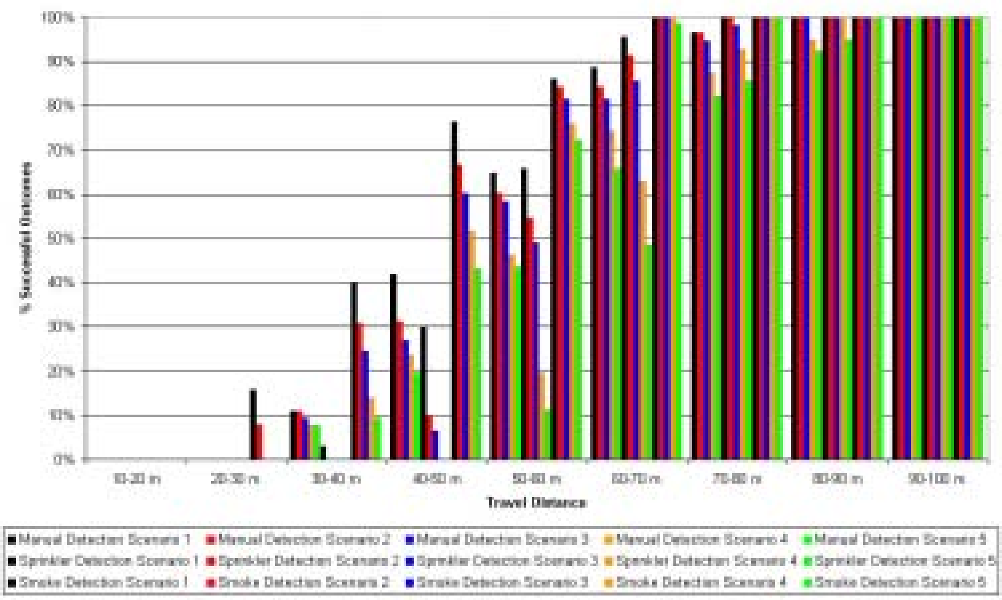

Figure 12.47 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Loveseat Fire

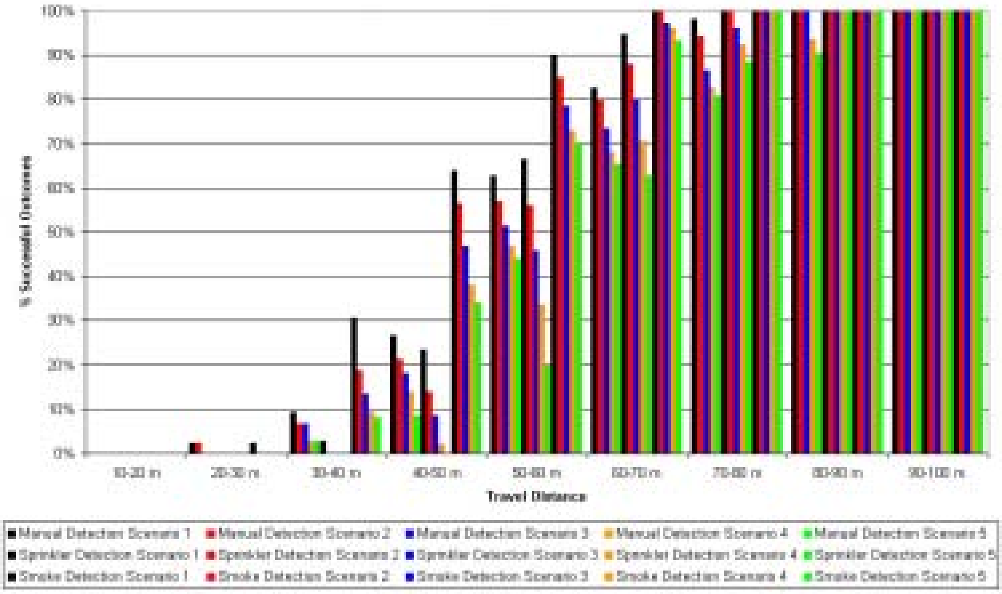

Figure 12.48 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Sofa Fire

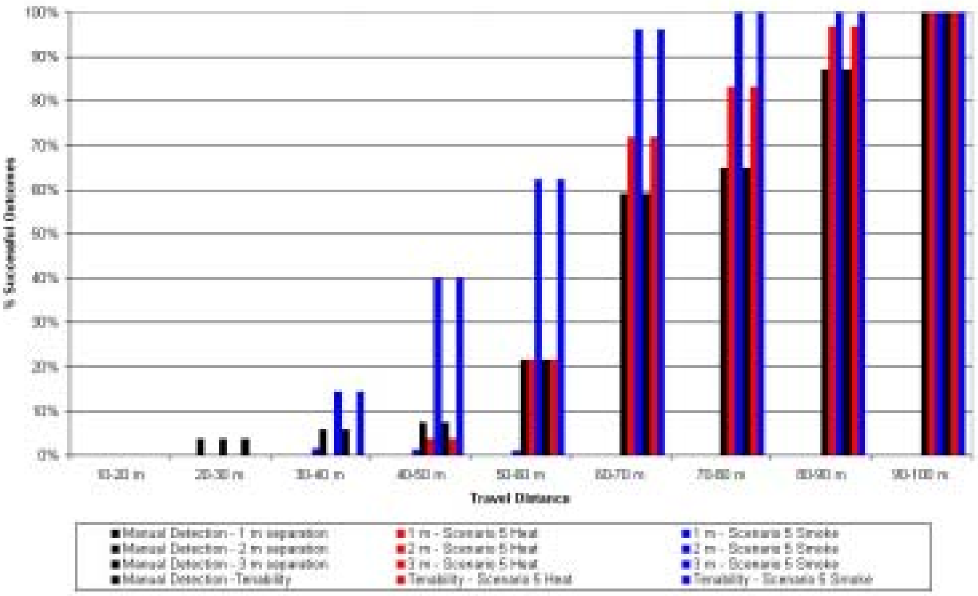

Figure 12.49 : Seated Crowd Environment Escape Scenario Outcome Comparison – Y5.0/14 Stackable Chair Fire

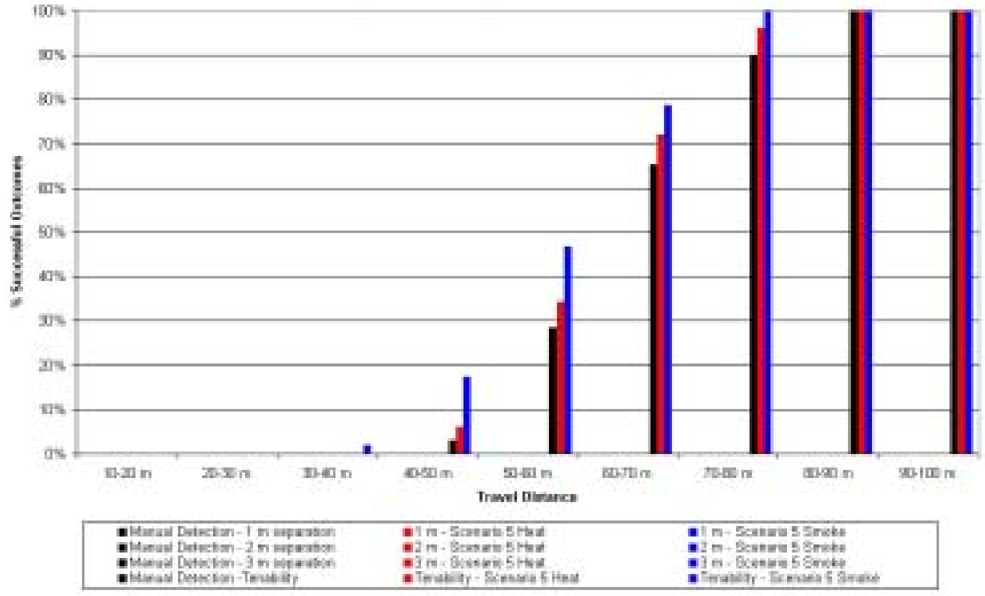

Figure 12.50 : Seated Crowd Environment Escape Scenario Outcome Comparison – Y5.3/10 Chair Fire

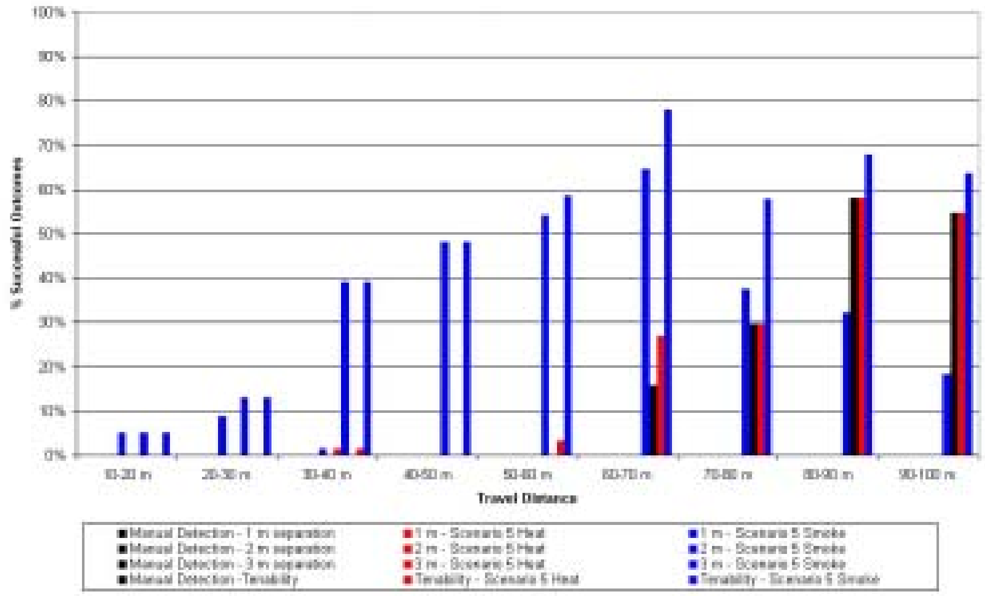

Figure 12.51 : Seated Crowd Environment Escape Scenario Outcome Comparison – Y5.4/21 Sofa Fire

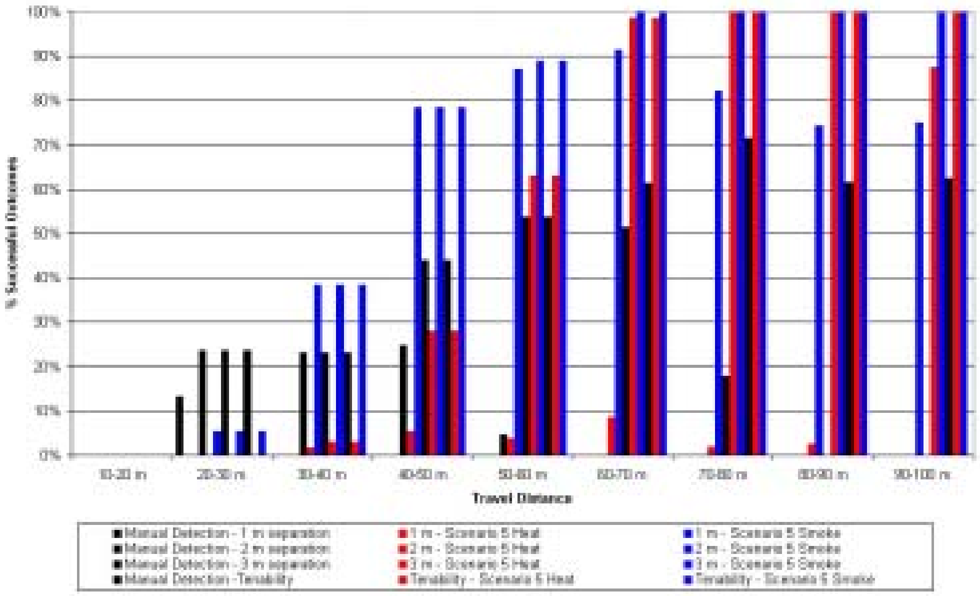

Figure 12.52 : Seated Crowd Environment Escape Scenario Outcome Comparison – Loveseat Fire

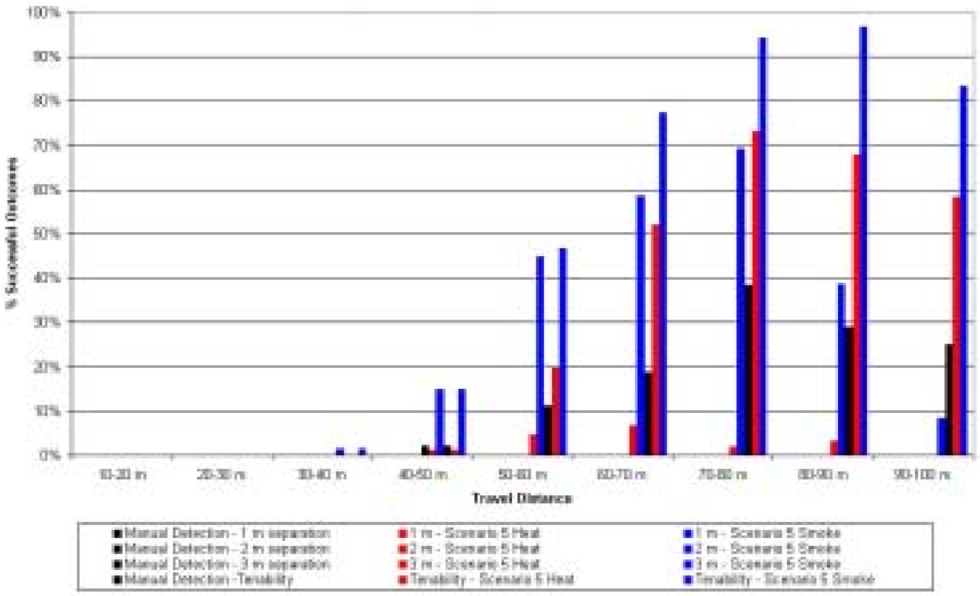

Figure 12.53 : Seated Crowd Environment Escape Scenario Outcome Comparison – Sofa Fire

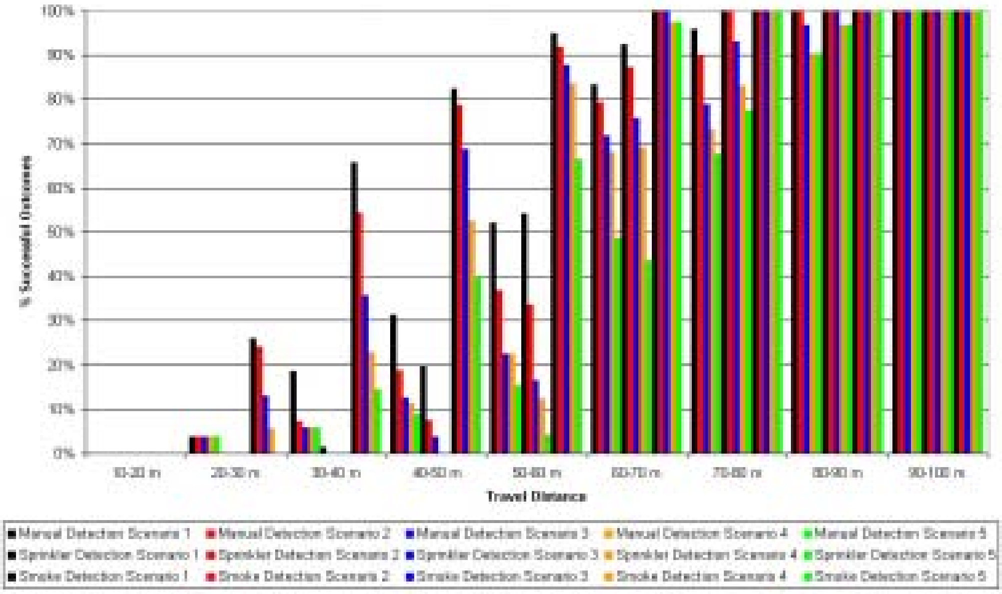

Figure 12.54 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison - Y5.0/14 Stackable Chair Fire

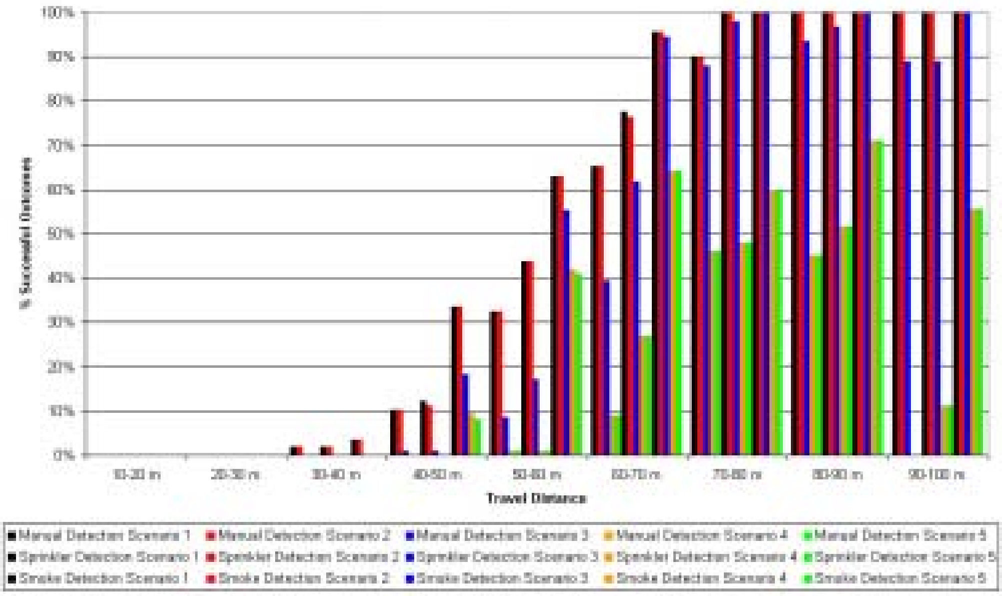

Figure 12.55 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y5.3/10 Chair Fire

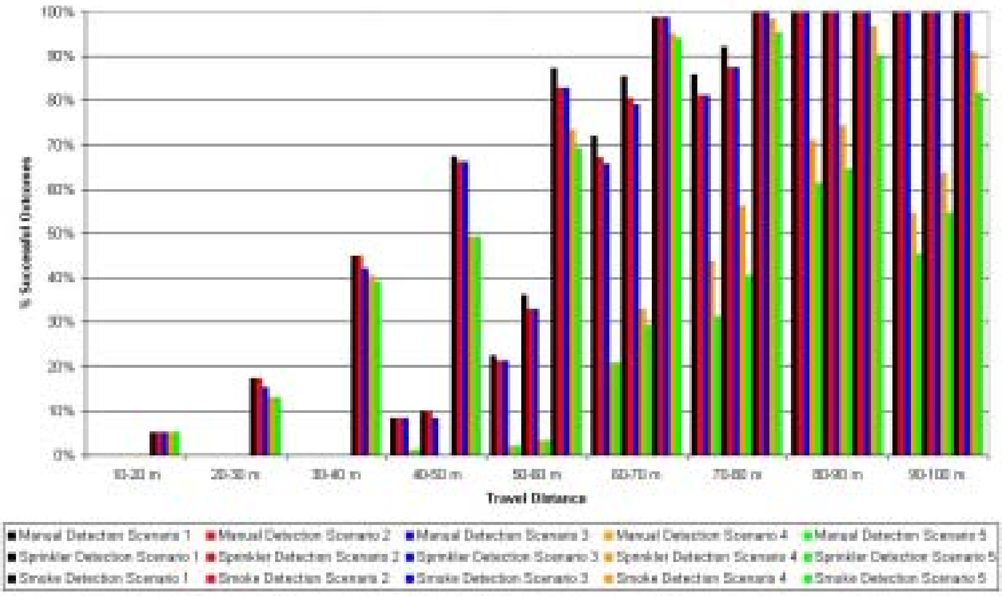

Figure 12.56 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y5.4/21 Sofa Fire

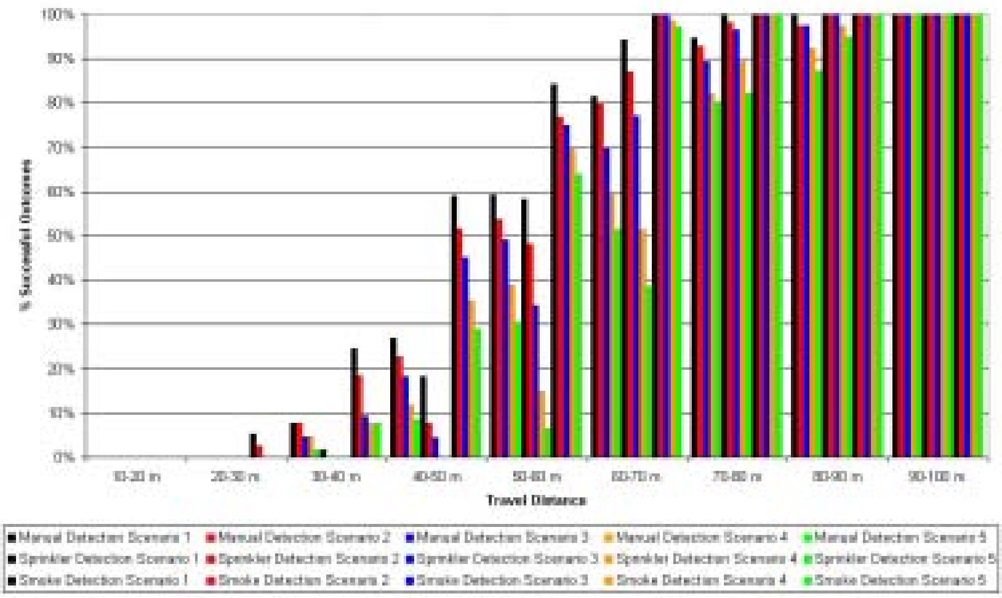

Figure 12.57 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Loveseat Fire

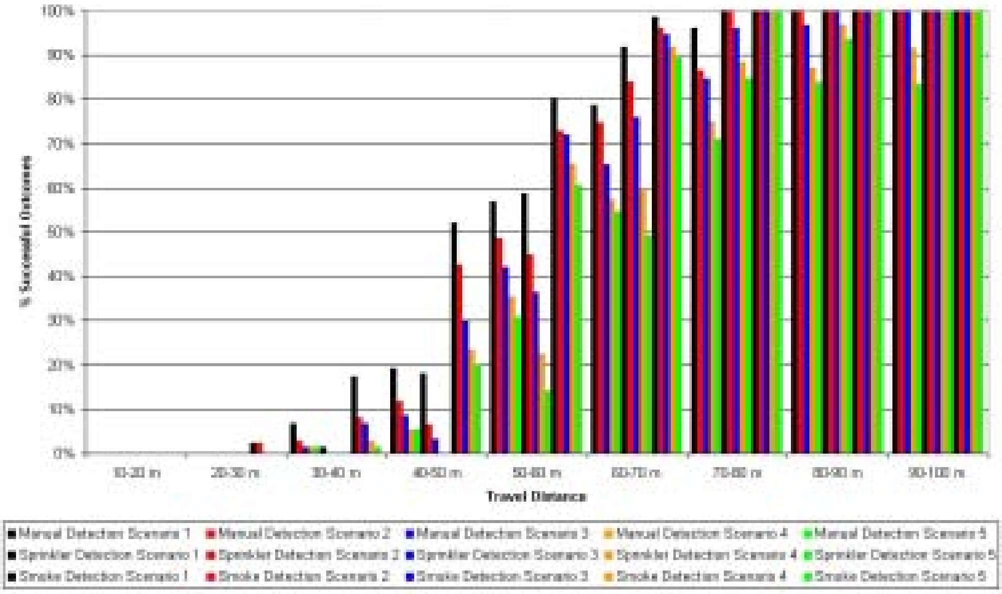

Figure 12.58 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Sofa Fire

<u>Storage Fires</u>

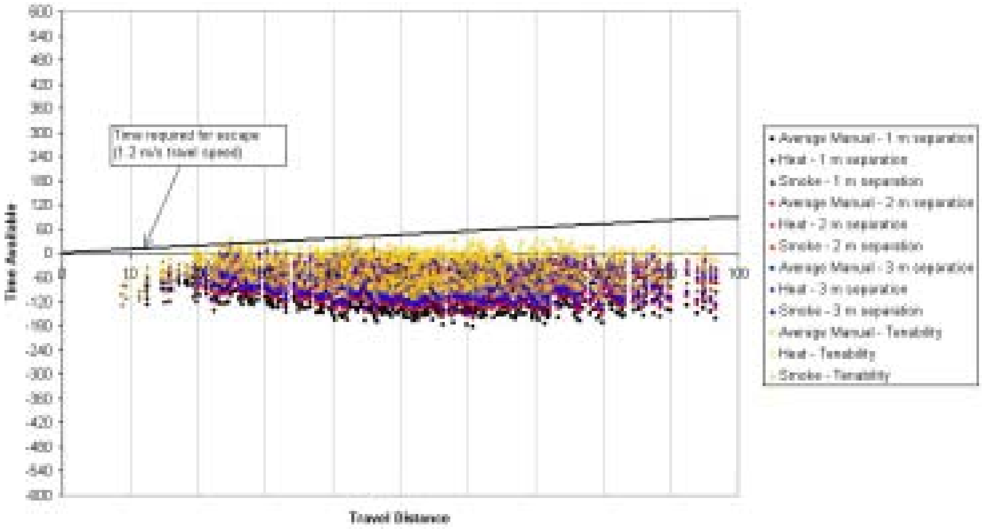

Figure 12.59 : Available Escape Time from Work Environment – Y3.1/13 Wardrobe Fire

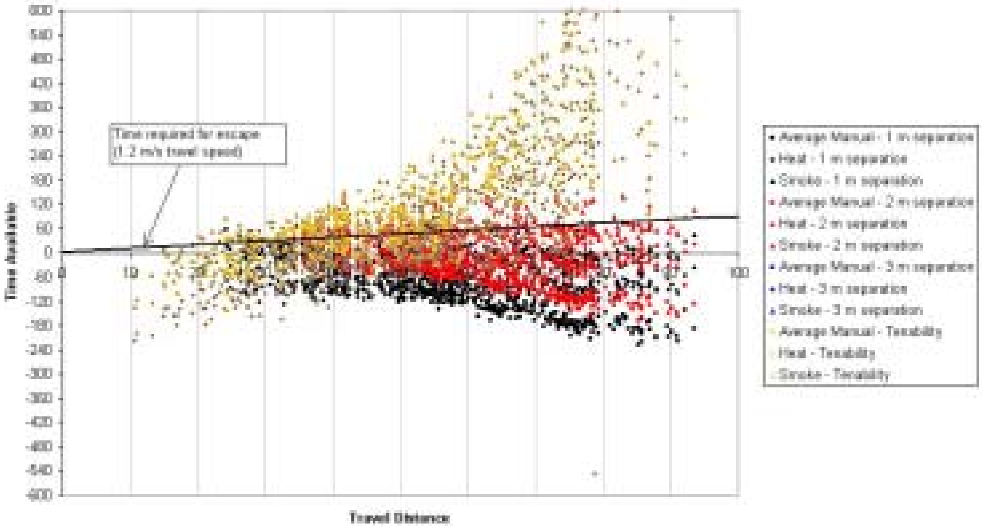

Figure 12.60 : Available Escape Time from Work Environment – Y3.3/13 Bookcase Fire

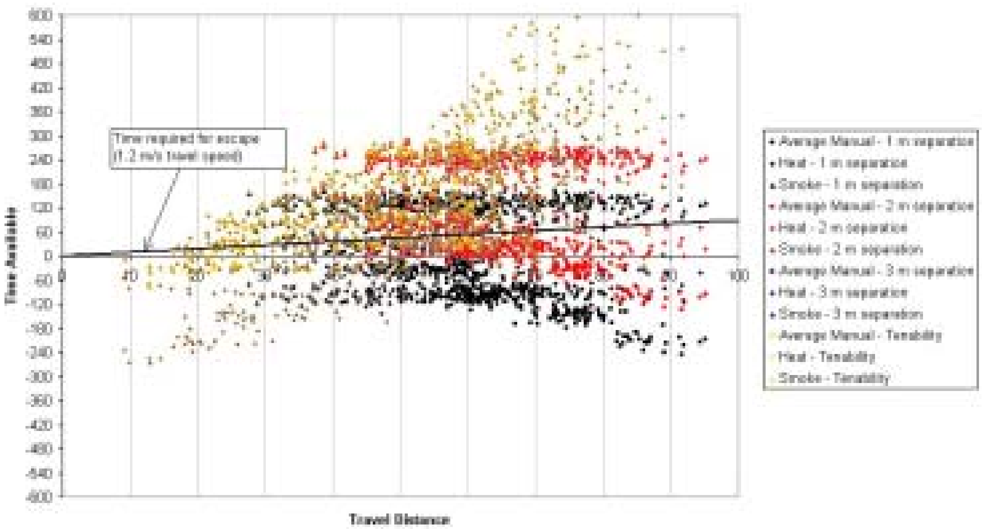

Figure 12.61 : Available Escape Time from Work Environment – Small Dresser Fire

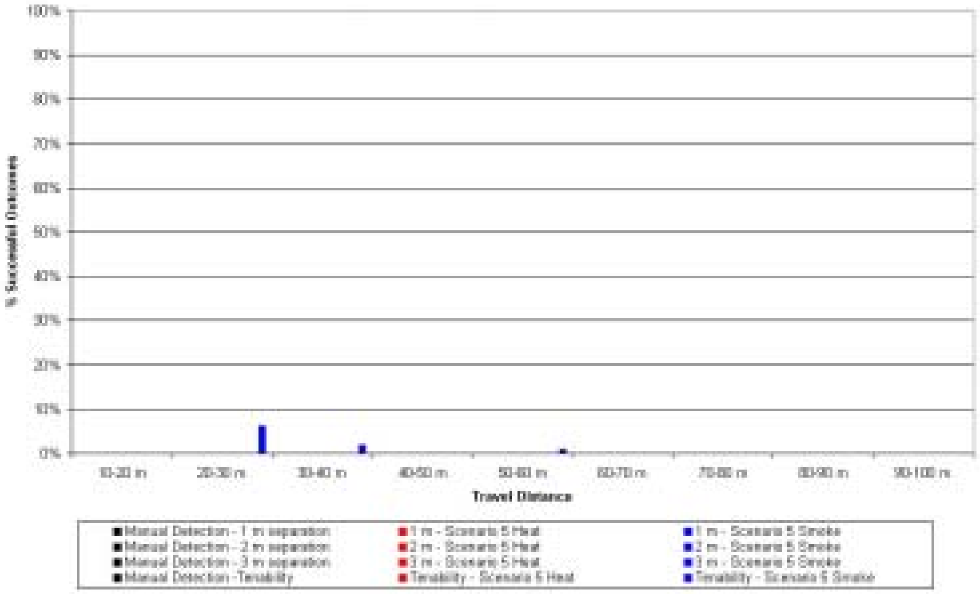

Figure 12.62 : Work Environment Escape Scenario Outcome Comparison – Y3.1/13 Wardrobe Fire

Note the scarcity of successful outcomes in the above graph.

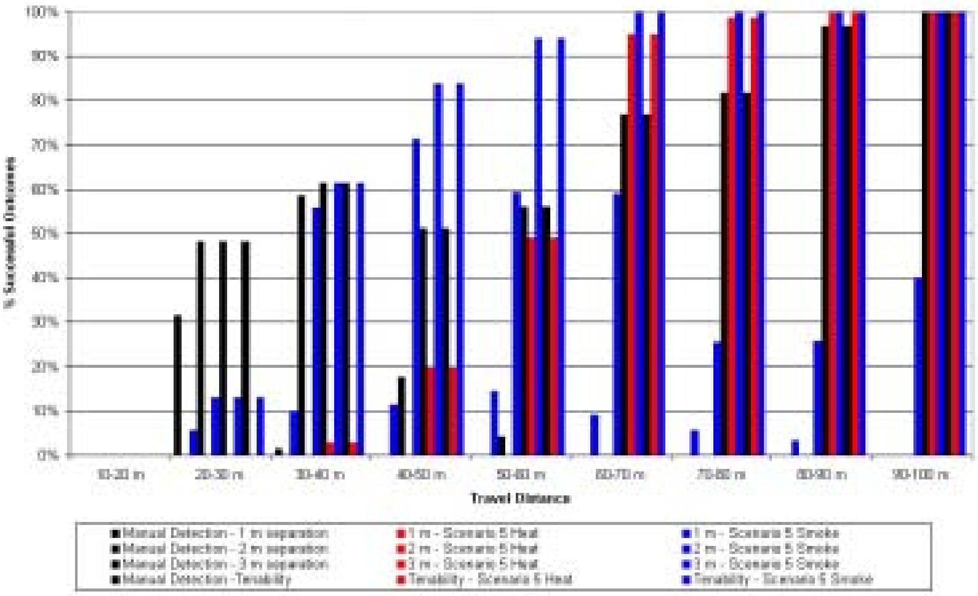

Figure 12.63 : Work Environment Escape Scenario Outcome Comparison – Y3.3/13 Bookcase Fire

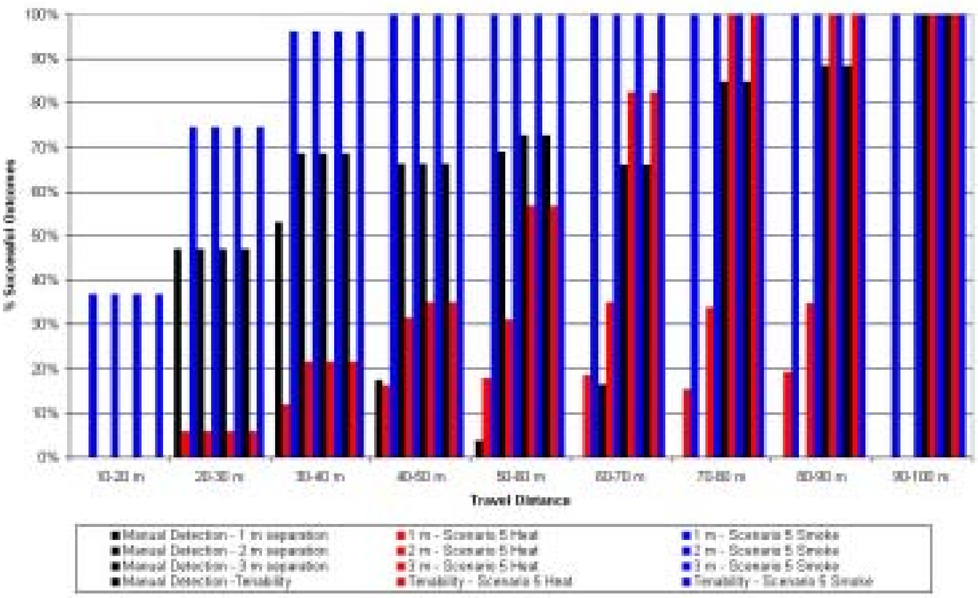

Figure 12.64 : Work Environment Escape Scenario Outcome Comparison - Small Dresser Fire

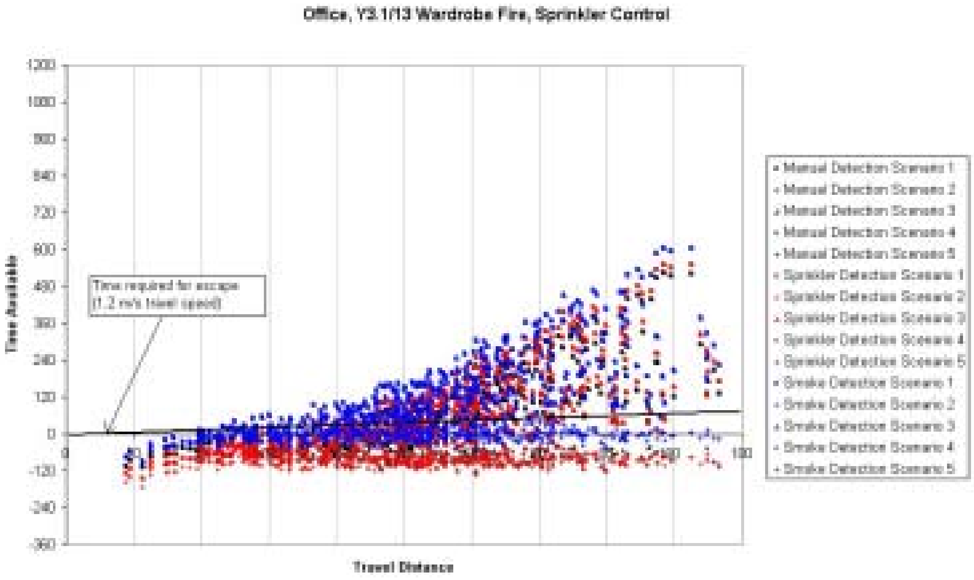

Figure 12.65 : Available Escape Time from Sprinkler Protected Work Environment – Y3.1/13 Wardrobe Fire

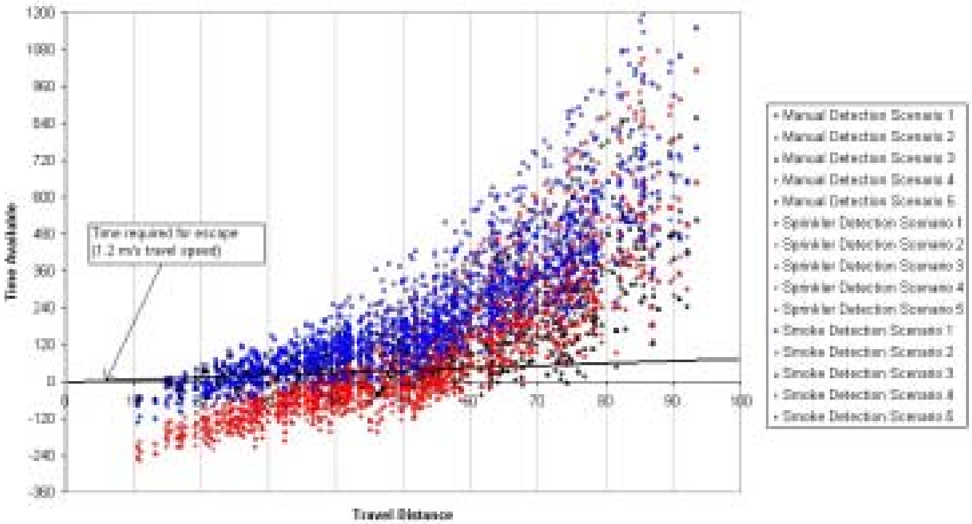

Figure 12.66 : Available Escape Time from Sprinkler Protected Work Environment – Y3.3/13 Bookcase Fire

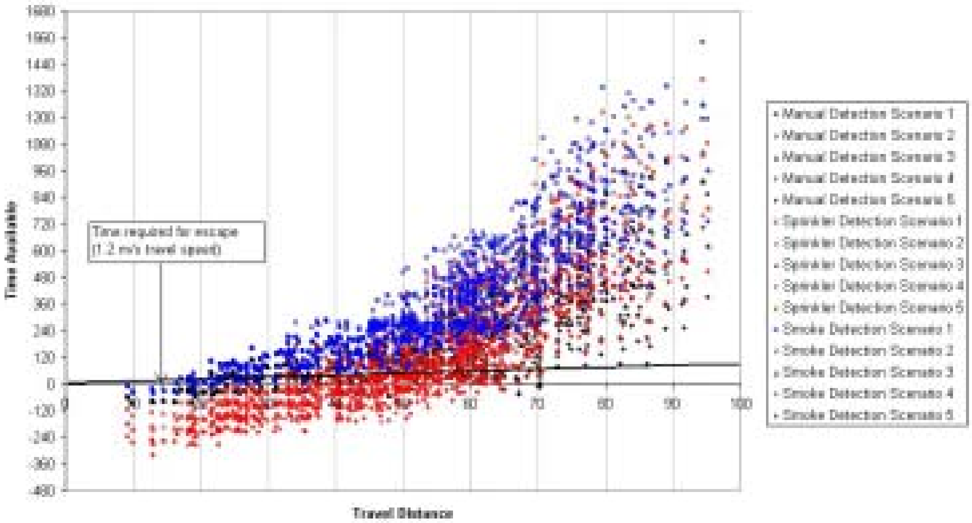

Figure 12.67 : Available Escape Time from Sprinkler Protected Work Environment – Small Dresser Fire

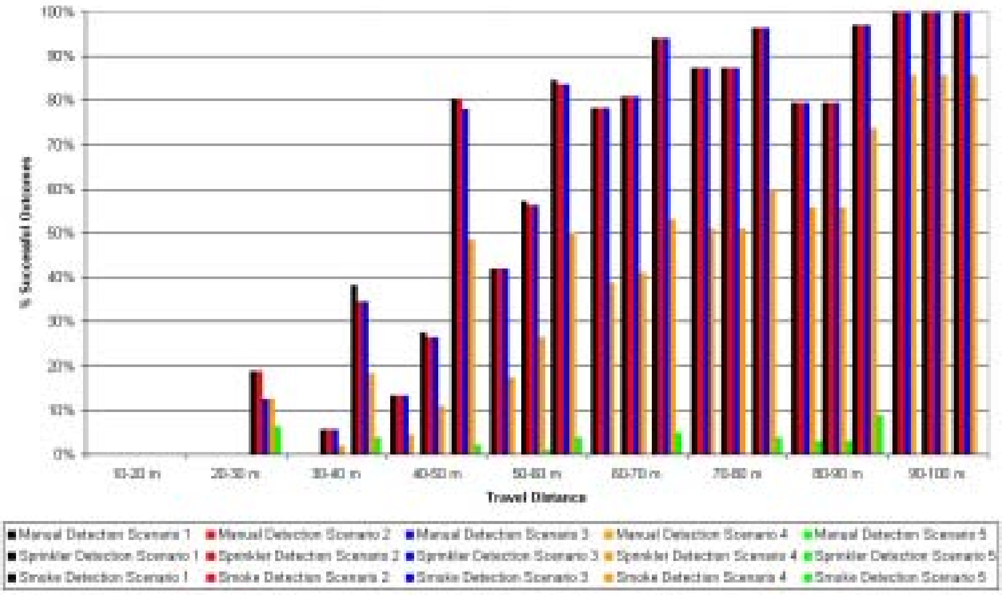

Figure 12.68 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y3.1/13 Wardrobe Fire

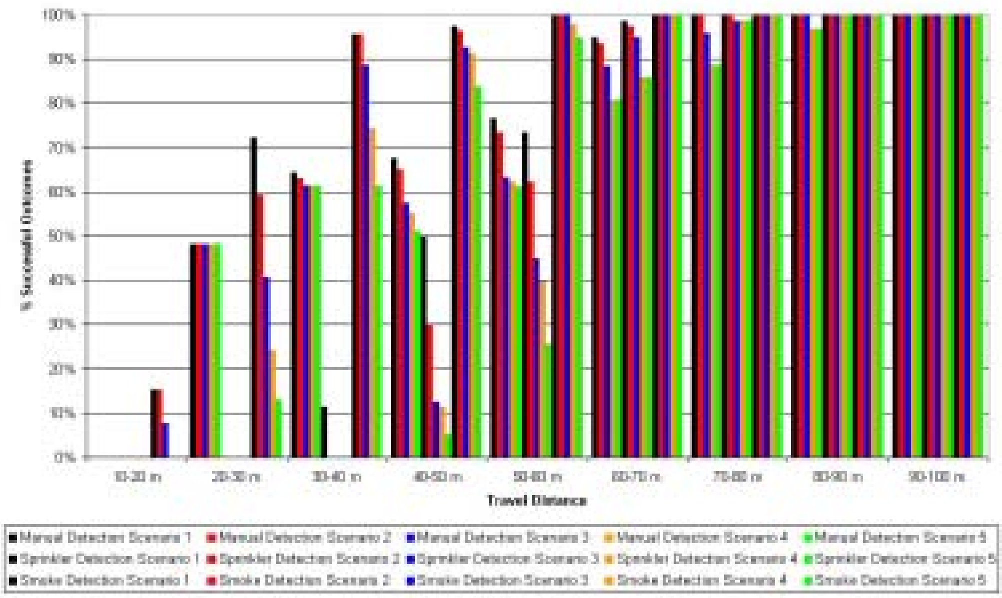

Figure 12.69 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y3.3/13 Bookcase Fire

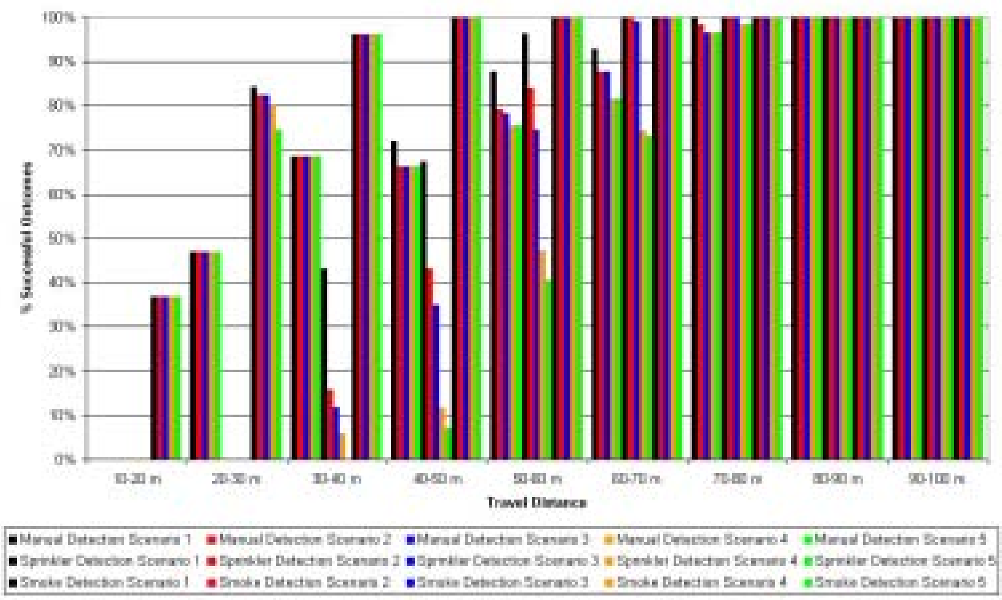

Figure 12.70 : Work Environment Sprinkler Protection Escape Scenario Outcome Comparison – Small Dresser Fire

No figure for Mobile Crowd Environment Escape Scenario Outcome Comparison – Y3.1/13 Wardrobe Fire has been included as there are no successful outcomes.

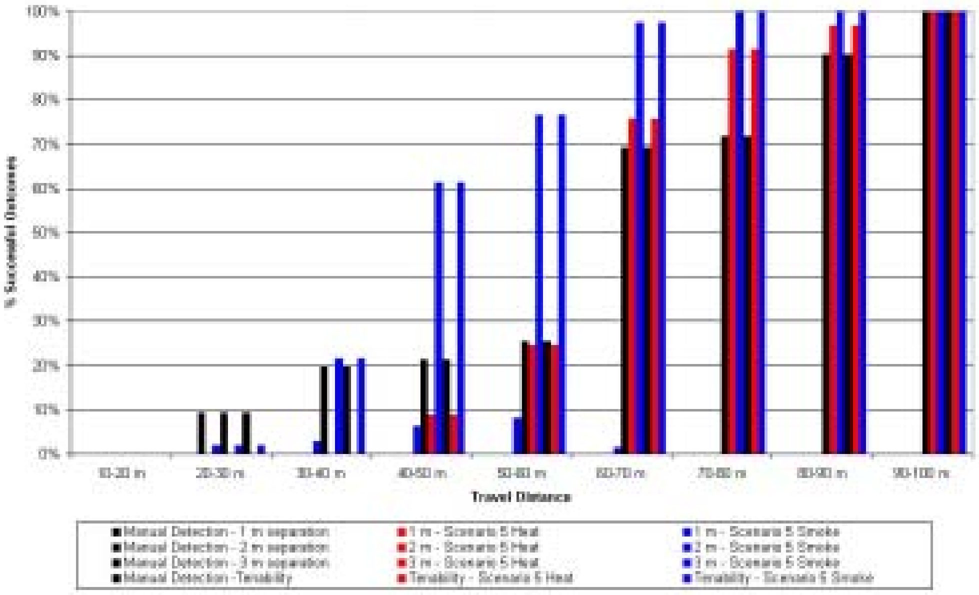

Figure 12.71 : Mobile Crowd Environment Escape Scenario Outcome Comparison – Y3.3/13 Bookcase Fire

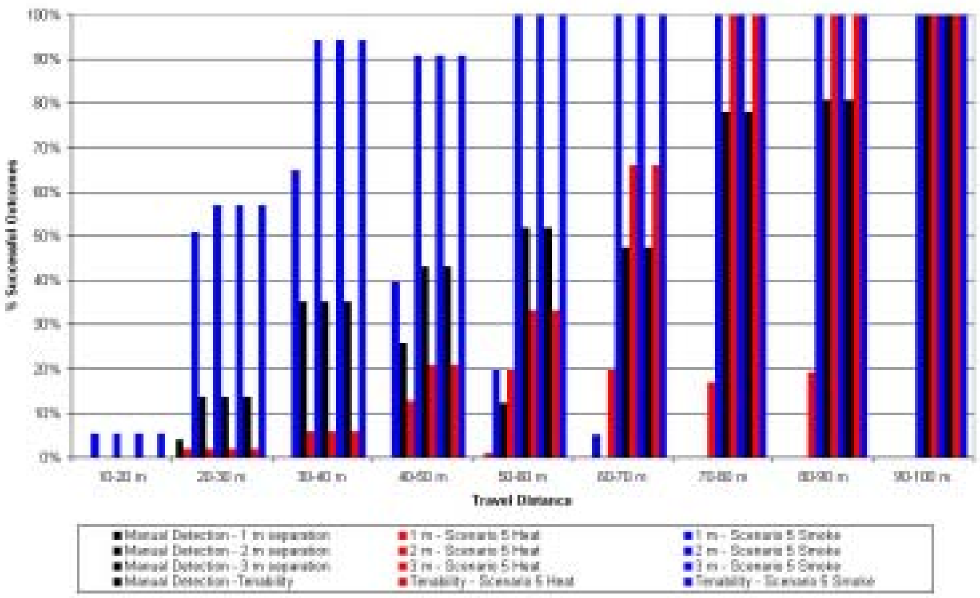

Figure 12.72 : Mobile Crowd Environment Escape Scenario Outcome Comparison – Small Dresser Fire

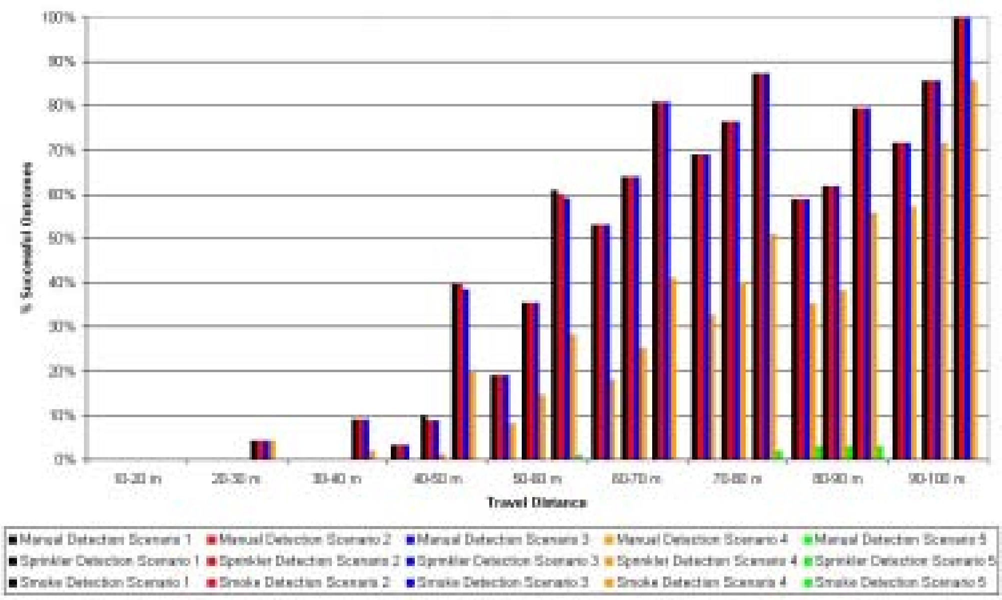

Figure 12.73 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y3.1/13 Wardrobe Fire

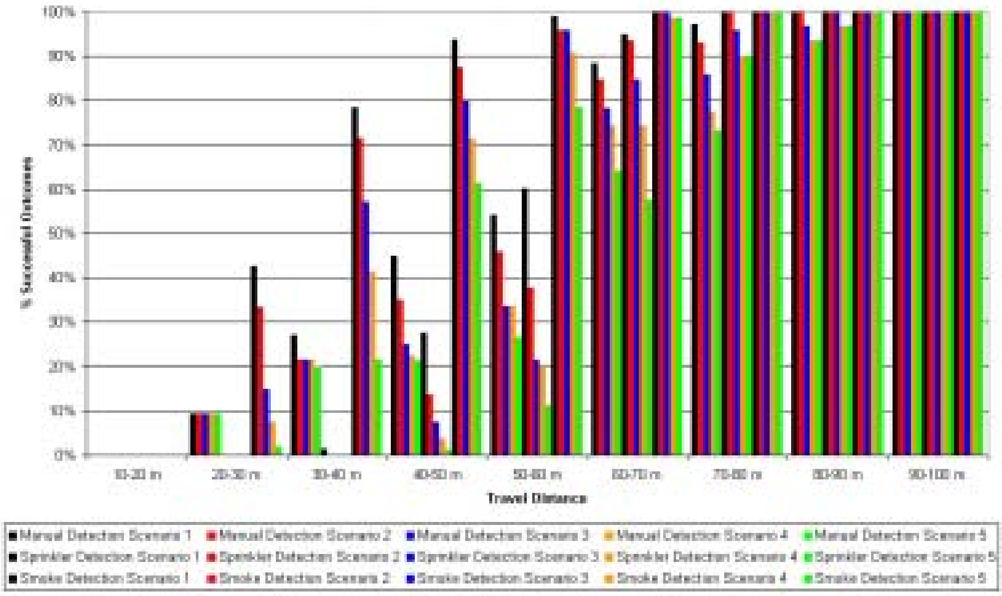

Figure 12.74 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y3.3/13 Bookcase Fire

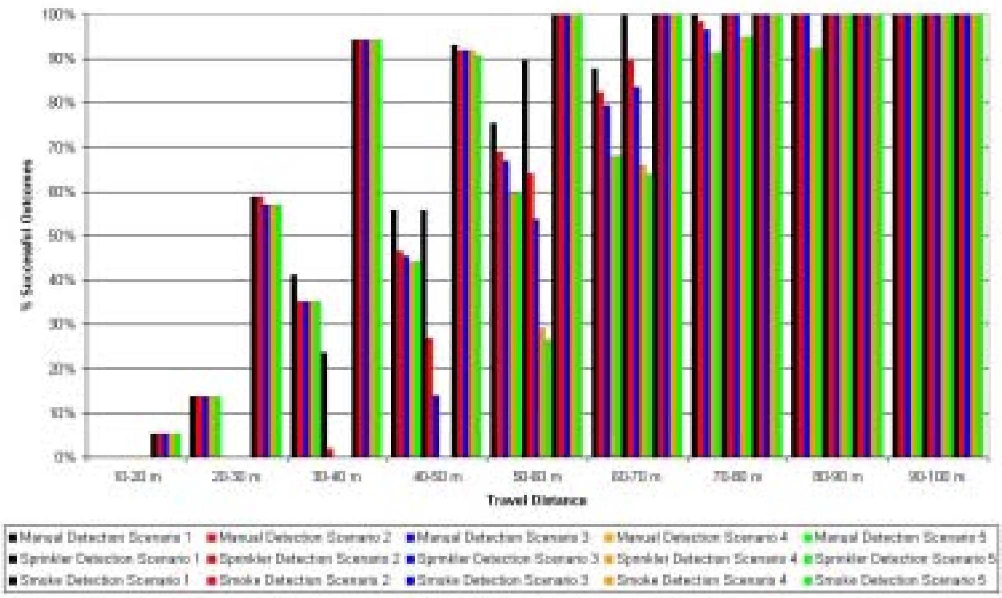

Figure 12.75 : Mobile Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Small Dresser Fire

A figure for Seated Crowd Environment Escape Scenario Outcome Comparison – Y3.1/13 Wardrobe Fire has not been included as there are no successful outcomes.

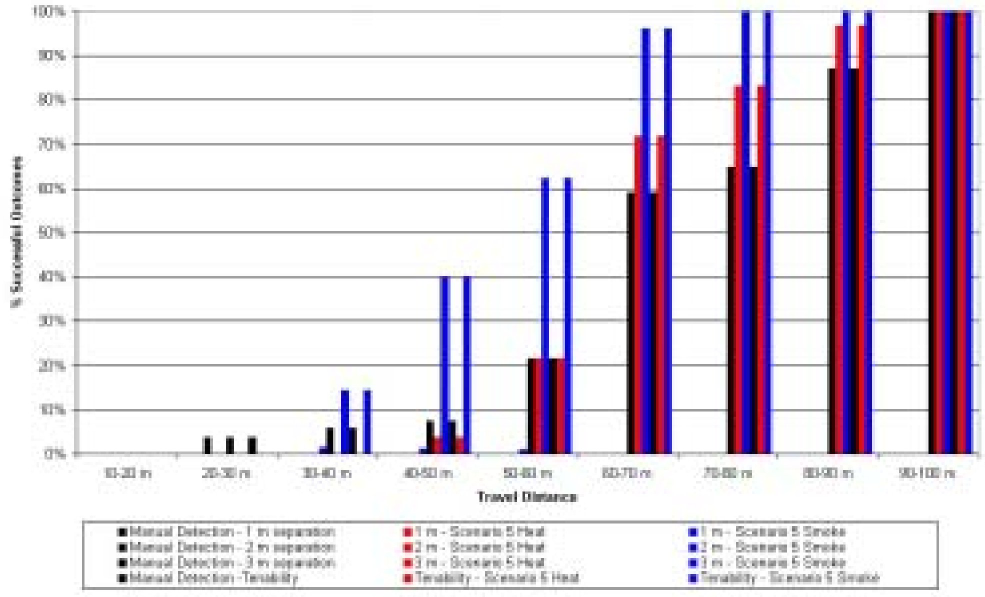

Figure 12.76 : Seated Crowd Environment Escape Scenario Outcome Comparison – Y3.3/13 Bookcase Fire

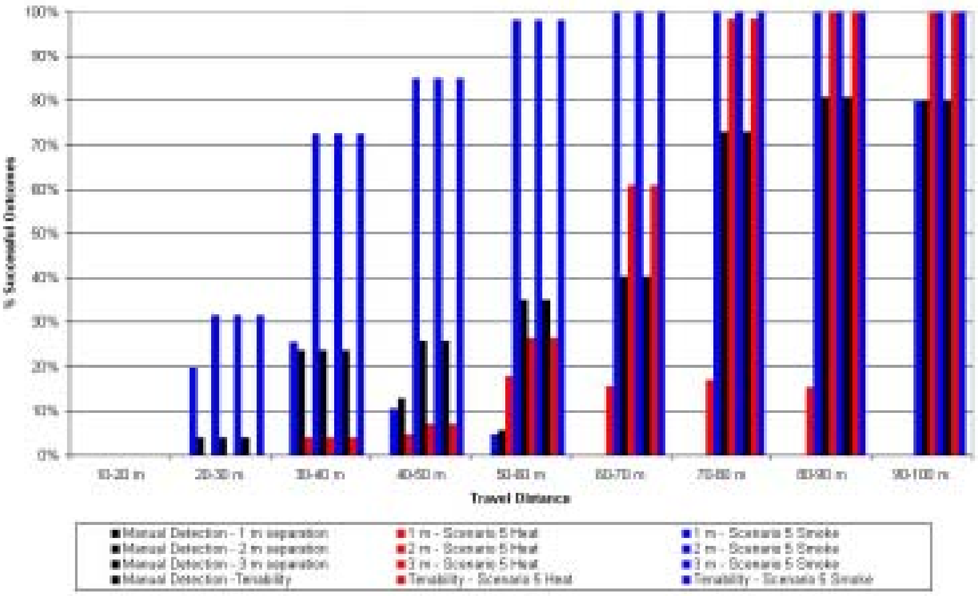

Figure 12.77 : Seated Crowd Environment Escape Scenario Outcome Comparison – Small Dresser Fire

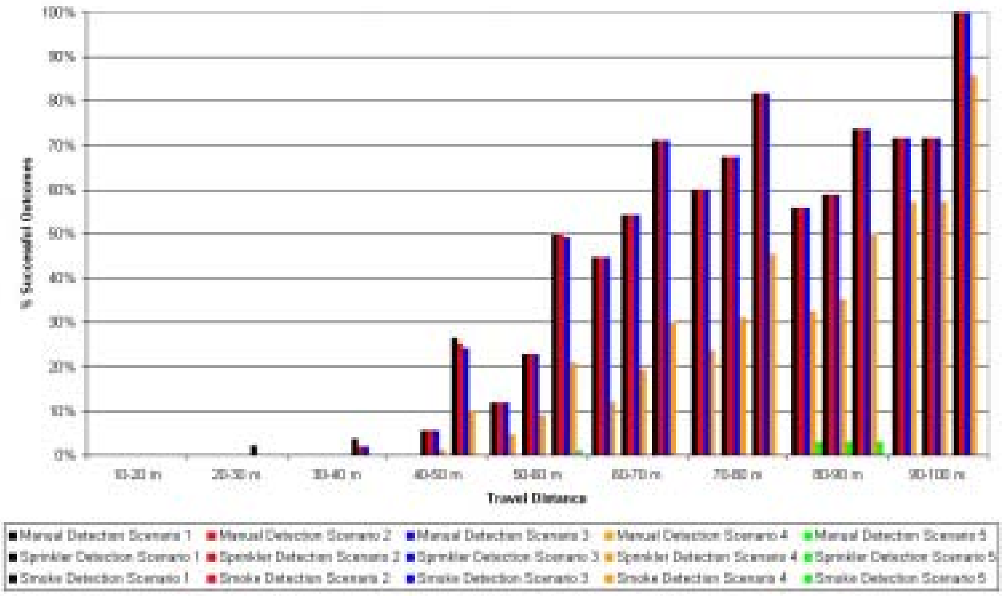

Figure 12.78 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y3.1/13 Wardrobe Fire

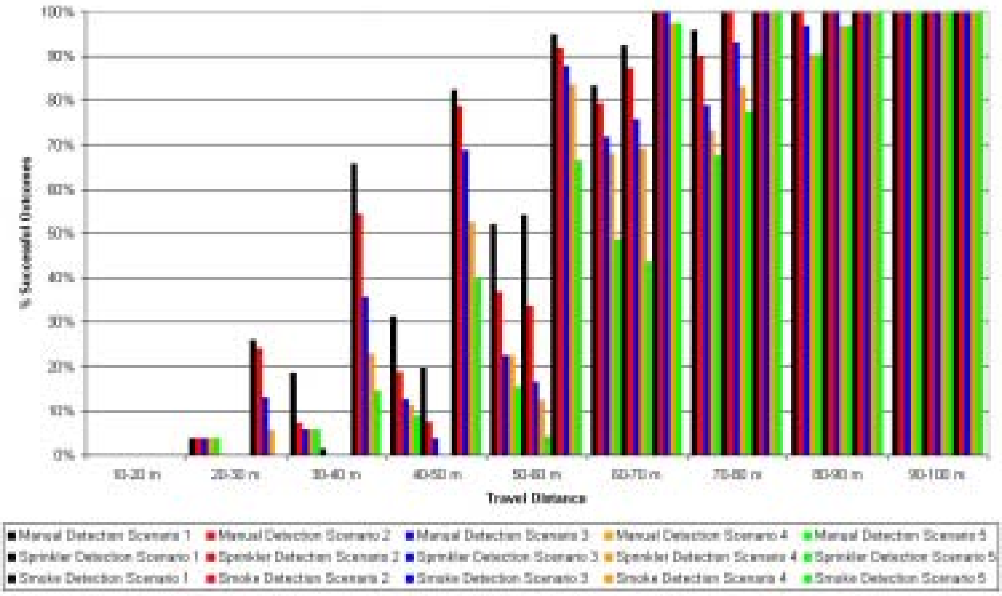

Figure 12.79 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Y3.3/13 Bookcase Fire

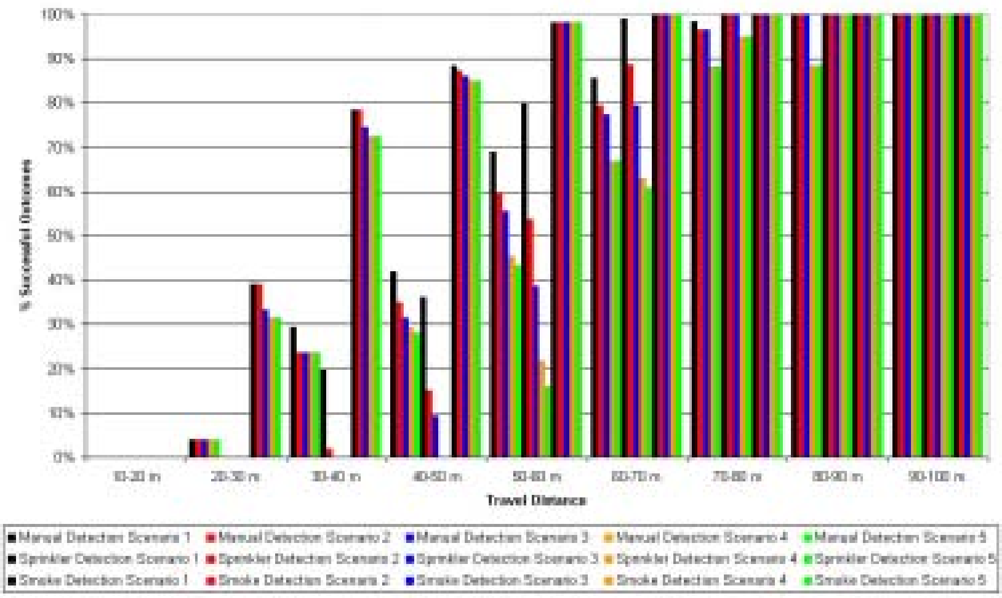

Figure 12.80 : Seated Crowd Environment Sprinkler Protection Escape Scenario Outcome Comparison – Small Dresser Fire